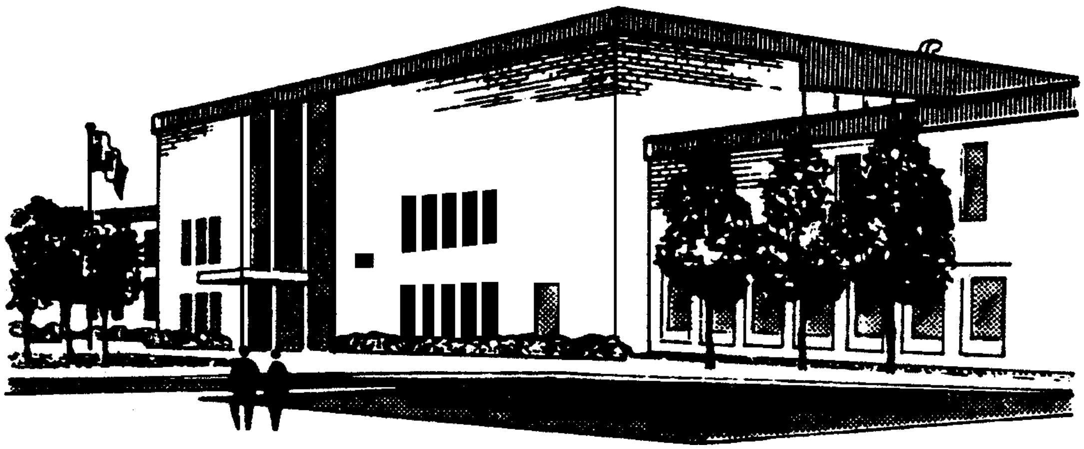
City of Houston Diesel Field Demonstration Project



ERMD Report # 01-36
ENVIRONMENTAL TECHNOLOGY CENTRE
EMISSIONS RESEARCH AND MEASUREMENT DIVISION

Environment Canada Environnement Canada

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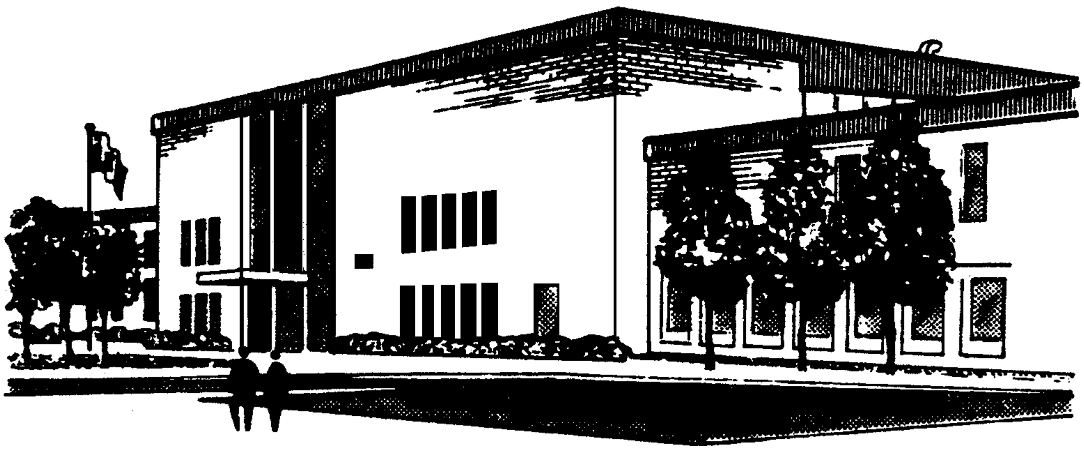

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EMISSIONS RESEARCH AND MEASUREMENT DIVISION

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1.0 ABSTRACT

Through the City of Houston's Emissions Reduction Plan (ERP)[1], http://www.ci.houston.tx.us/citygovt/mayor/cleanair.pdf, the City has been charged to investigate the potential of various emission control technologies and develop strategies to minimize the pollution contribution of its own fleet. This report describes the research that was undertaken to quantify the effects of various modified diesel fuels and retrofit emission control technologies on the exhaust emission rates of a variety of city vehicles operated over their representative duty cycle. An evaluation of the results is provided for both the original baseline vehicle configuration as well as with the modified diesel fuels and retrofit exhaust after-treatment. All of the testing was undertaken "in-the-field" using a portable emissions sampling system developed by Environment Canada that facilitates the collection of emissions data while the equipment is operated under real world conditions.

2.0 INTRODUCTION

2.1 Background

The Houston-Galveston area is presently classified as a Severe-17 Ozone non-attainment area under the Federal Clean Air Act (FCAA) Amendments of 1990 (42 United States Code (USC) 7401 et seq.). Therefore the region must attain the 1-hour ozone standard of 0.12 ppm by November 15th, 2007[2]. Failure to meet this objective could severely impact the region through the potential loss of Federal transportation funds, increased health costs, and other socio-economic impacts associated with air pollution.

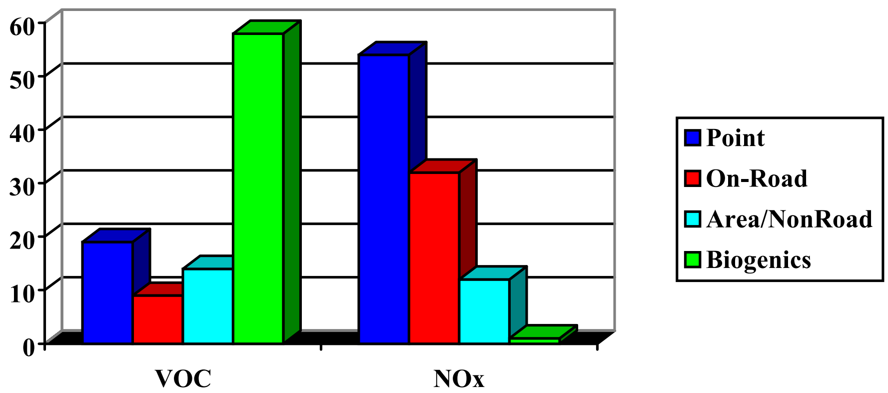
Since 1990, the State, together with Houston-Galveston Area Council (H-GAC), other affected regions, and various stakeholders, have been working to develop a State Implementation Plan (SIP) that would result in obtaining compliance with the 1-hour ozone standard. One of the first steps in developing the SIP was to characterize the ozone issue through various efforts including source inventories, air quality monitoring, and air quality modeling.

Ozone is formed through a series of photochemical reactions in the presence of heat and sunlight primarily involving volatile organic compounds, NOx, and to a much lesser extent, carbon monoxide. Hence it is important to understand where these emissions are coming from, and which is the limiting factor in the generation of ozone for the region. Once the issue had been characterized to a satisfactory degree the various stakeholders in the region could then begin to develop and evaluate local control strategies using the available models.

[1] Emissions Reduction Plan, City of Houston, July 2000, 000726 LPB memo to council
[2] Revisions to the State Implementation Plan (SIP) for the Control of Ozone Air Pollution. Texas Natural Resource Conservation Commission. September 12, 2001

Figure 1 illustrates the outputs from the baseline inventory studies undertaken by the region for a 1993 base case year[1].

Figure 1 1993 Base Case Year, Percent Contribution to Total NOx Emissions



From this Figure it is clear that the greatest contribution of NOx is from man-made sources while for VOC's it is from biogenic sources such as crops, lawn grass, and forests. When this data is forecast to 2007 the total VOC emissions decrease from 2213 to 1918 tons per day, while NOx emissions decrease from 1284 to 1104 tons per day.

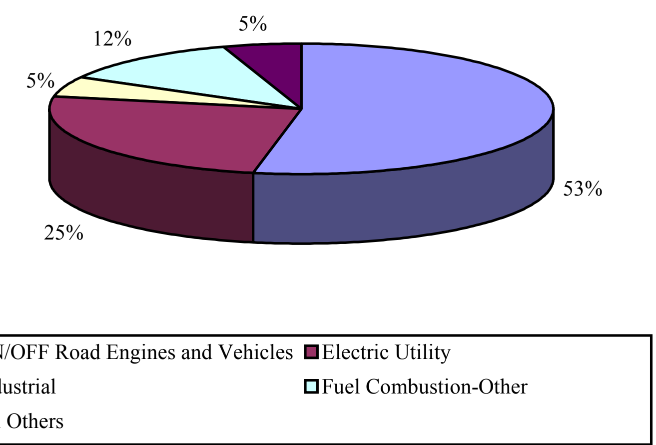
2.2 NOx Emission Sources

In an emission inventory there are a number of source types to be considered. In this case the sources can be segregated into the following categories[1];

- Point Sources: industrial, commercial, or institutional emitters which produce levels of criteria pollutants at or above prescribed amounts,
- On-Road Mobile Sources: This is comprised of vehicles operating on public roadways,
- Area Sources: commercial, small-scale industrial, and residential categories of sources that use materials or operate processes that can generate emissions below the levels described for point sources. The emission vector, through fuel/solvent evaporation or through combustion, can further define these sources.
    - Non-Road Mobile Sources: This sub-set of the Area Source category is very broad, including aircraft operations, engines used in marine, and railway systems, as well as all non-highway equipment used in agriculture, construction, and other applications.
    - Biogenic Sources: This is a sub-set of the Area Source category, and addresses the VOC emissions from crops, lawns, and forests, as well as the small amount of NOx emitted from soils.

In the previous Figure it is evident that the emission sources of NOx is predominantly from combustion as opposed to biogenic. The NOx emissions are a by-product of combustion however there are a number of combustion sources. Figure 2 illustrates the principal source category contribution of NOx to the national inventory as reported by the United States Environmental Protection Agency (USEPA)[3].

Figure 2 Principal Source NOx Category Contributions



The USEPA has estimated that on-road vehicles account for 31% of the total national NOx emission, and approximately 37% of this is attributed to light duty gasoline vehicles, and 35% attributed to diesel vehicles. The non-road engines and vehicles account for 22% of the total inventory, with 53% of those emissions (not including marine, locomotive and aircraft) attributed to diesel usage in construction, agricultural and other applications.

2.3 Diesel Combustion NOx Emissions

Diesel engines differ from gasoline engines in that they utilize compression to ignite the air/fuel mixture as opposed to a spark source. This higher compression results in much higher temperatures in the region of the combustion and as a consequence the oxygen and nitrogen in the intake air combine to form NOx. Typically, diesel NOx emissions are 1.5 to 2.0 times higher than those from comparable gasoline vehicles[4].

Diesel engines are undergoing considerable design changes including higher fuel injection pressures, more use of turbo-charging and charge air inter-cooling, retarded injection timing, electronic engine controls, revised combustion chamber design, improved lube oil control, and exhaust after-treatment devices. These design modifications affect the relationship between fuel properties and emissions. Therefore, relationships between exhaust emissions and fuel properties must be continually updated to correspond with the improvements in engine design that have occurred in the last few years.

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[3] National Air Pollutant Emission Trends, 1990-1998. EPA-454/R-00-002 March 2000

[4] Regulatory Impact Analysis: Heavy Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control requirements. USEPA December 2000

Further improvements are likely to result from a combination of technologies, but primarily through more precise control of the combustion process using on-board computers and improved fuel injection. However, there may be limits to what can be achieved as there is a tradeoff between the combustion conditions that give rise to low particulate emissions and those that give rise to low NOx emissions. Reducing emissions of one will typically increase emissions of the other. Although the evolution of new technology has reduced these trade-offs, in the future exhaust after-treatment devices may be required to reduce emissions even further. These may be used either to reduce the NOx emissions, allowing engine design to be optimized to reduce particulates, or more likely, to reduce the levels of exhaust particulate matter allowing the engine to be optimized for low NOx operation through exhaust gas recirculation (EGR).

2.4 Diesel Combustion Particulate Matter Emissions

Diesel particulate matter (DPM) is comprised of soot (carbonaceous solid matter), heavy hydrocarbons, and sulfate particulates. Particulate matter from diesel engine combustion is of special concern due to the impact the material has on health. DPM is known to aggravate lung diseases such as asthma, emphysema and bronchitis. Due to the size of the particulate material, (over 90% of diesel particulate are less than 1 micron in size), it is easily inhaled and deposited deeply within the lungs. The material has exhibited mutagenicity in biological testing and known carcinogenic compounds have been isolated from the matrix of compounds that comprise DPM.

2.5 Diesel Emission Control Technologies

There are a number of technologies or strategies that have been developed that have the potential to meet or exceed the increasingly stringent NOx and/or Particulate Matter (PM) regulatory requirements. In most cases these technologies share a common requirement that the diesel fuel have lowered sulfur content. The fuel sulfur concern is two fold; firstly it contributes to the overall mass of the particulate emissions, while secondly and perhaps more importantly the sulfur has a detrimental effect on the functionality of the advanced catalytic control systems. Some of the more common systems to be considered for retrofit emission control are briefly described in the following sections;

2.5.1 Diesel Oxidation Catalysts (DOC)

These systems are designed to reduce the hydrocarbon and carbon monoxide emissions in the exhaust gas as well as the organic fraction of the particulate matter. This organic fraction may be comprised of fuel or oil based hydrocarbons that have survived the combustion process and have been absorbed onto the carbon core of the particulate material.

2.5.2 Diesel Particulate Filters (DPF)

These systems remove diesel particulate from the exhaust stream by collecting the material on a filter element that is typically constructed from a porous ceramic material.

The particulate in the exhaust is forced through the porous ceramic walls before leaving the filter. This traps the particulate on the porous ceramic walls. However, a 'simple' filter would rapidly become blocked and eventually exert high backpressure on the engine. This could potentially cause an increase in fuel consumption as well as emissions, and eventual stalling or engine failure. It is therefore necessary to periodically clear the trap of particulates. This can be achieved through a number of approaches and is referred to as 'regeneration'. Regeneration occurs when a catalyzed DPF has been coated with catalyst material that oxidizes the exhaust hydrocarbons and carbon monoxide in the exhaust stream, as well as those hydrocarbons adhering to the trapped particulate matter. This results in a continuous regeneration of the filter. An oxidation catalyst placed upstream of the filter has also been shown to facilitate trap regeneration by emitting nitrogen dioxide, which oxidizes the particulate entrained in the ceramic filter.

2.5.3 Exhaust Gas Recirculation (EGR)

Exhaust Gas Recirculation is a technique for reducing NOx emissions that has been used in spark ignited engines for many years. When nitrogen is exposed to very high temperatures and pressures, as in the combustion chamber, nitrogen becomes reactive and combines with oxygen to form NOx. The EGR system controls NOx emissions by keeping the combustion temperature below that at which NOx is formed. To achieve this a small amount of exhaust gas is re-routed into the intake cycle to dilute the intake air, reducing the oxygen content of the combustion mixture and therefore reducing the combustion temperature. The quantity of exhaust gas that is re-introduced must be carefully controlled as too much gas can result in increased particulate and carbon monoxide emissions due to insufficient air for complete combustion to occur. The primary obstacle to incorporating EGR into the diesel engine has been the presence of particulate matter in the exhaust stream. This material can have a deleterious effect on the flow metering systems as well as the internal engine components. The significant reduction in engine out particulate in recent years, as well as progress in exhaust particulate control systems, have made EGR a reality for new diesel engines and retrofit EGR systems are now in the field.

2.5.4 Lean-NOx Catalysts (LNC)

These catalysts reduce the NOx in the exhaust by providing sites where the hydrocarbons and NOx in the exhaust stream can react to form nitrogen, carbon dioxide and water, ideally the only products of combustion. The diesel engine has very low emission rates of hydrocarbons and therefore a secondary source of HC's are necessary to create the necessary environment for these catalysts to function. Injecting precise quantities of fuel into the exhaust, and including an oxidation catalyst in the system for added control after the LNC achieve this. This technology is very sulfur sensitive.

2.5.5 Diesel-Water Emulsions

This fuel-based strategy relies upon water blended in the fuel to minimize the number of elevated temperature regions in the engine during combustion. This has the positive effect of reducing NOx formation; however there may be a power loss as the energy density of the fuel is lowered. The primary challenge is to formulate an additive package that prevents separation of the materials. Recent work has also indicated that this technology has an impact on the particulate emissions.

2.5.6 Selective Catalytic Reduction Devices (SCR)

SCR technology involves the selective catalytic reduction of NOx, using ammonia (NH_3) or urea, as the reducing gas, injected into the exhaust stream with an electronic controlled diffusion system and passed over a specially formulated catalyst-coated substrate. During this process, NOx is converted to nitrogen and oxygen by reaction with the NH_3. Fuels with high sulfur content can cause plugging and corrosion of downstream SCR equipment when reacting with the NH_3.

2.5.7 Selective Non- Catalytic Reduction Devices (SNCR)

SNCR technology involves a reducing agent, typically NH_3 or urea, being injected into the exhaust manifold with an electronic controlled diffusion system where it reacts with the exhaust stream to reduce NOx emissions.

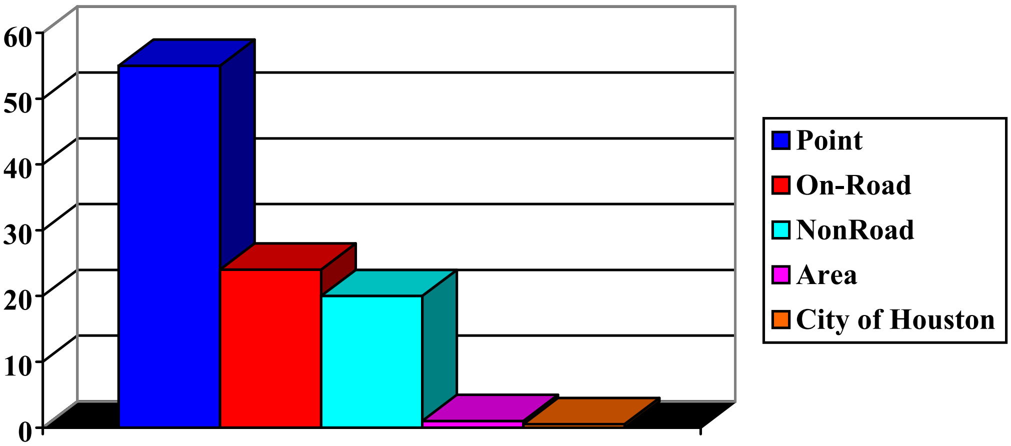
2.6 City of Houston Emissions Reduction Plan

In June 2000, the City of Houston established a comprehensive Emission Reduction Plan (ERP), http://www.ci.houston.tx.us/citygovt/mayor/cleanair.pdf, to address the air pollution contribution from each City department. The overall objective of the ERP is an aggressive 75% reduction in the NOx emissions, the largest man-made contribution to ozone precursors. A cornerstone of the plan is the Diesel Field Demonstration Project.

Under the Diesel Field Demonstration Project a number of diesel catalysts and other emission control systems were to be evaluated in the field on various vehicles and equipment from the summer of 2000 through to the fall of 2001. The intent was to identify retrofit emission control systems capable of achieving 75% NOx reductions concurrent with a reduction of fine particulate (PM2.5) by at least 25-33%. It was anticipated that the results of the study would support the decision making process by the city to retrofit the proven systems into the existing fleet where applicable.

While it is recognized that the city fleet represents a small fraction of the total overall vehicle population in the area, see Figure 3, it is hoped that by taking on the task and cost of demonstrating achievable emission reductions, other fleet operators and stakeholders will follow. The results and experiences of the program will contribute to a "how to" case study from which other stakeholders can follow and benefit.

Figure 3 1996 NOx Emission Sources in HGA, Percent of Total



Under the Diesel Field Demonstration Project a total of twenty-nine units were selected to be representative of the fleet, twenty-six of which were subjected to emissions testing in the field by Environment Canada as described in the following sections of the report.

3.0 TEST DESCRIPTION

Environment Canada conducted the gaseous and particulate exhaust emissions testing of the City of Houston fleet vehicles at Ellington Field, Houston, Texas. The vehicles were delivered to the test site by the appropriate City department. A detailed inspection of the vehicle's exhaust system, air intake, and overall integrity was undertaken upon delivery to the test site. The location for mounting the exhaust emission sampling system was determined and the equipment installed on the vehicle. In situations where it was not possible to mount the sampling system on the vehicle, a small utility trailer was used. Set up included installing the engine speed pick-up, exhaust temperature thermocouple, engine air intake measurement device, heated sample line with exhaust sample probe and portable computer. Once the sampling system was installed on the test vehicle a thorough systematic quality assurance program was initiated. This ensured proper operation of all solenoid valves, pressure transducers, thermocouples, flow controllers and associated electronic components of the system. Once the sampling system verification was complete the test vehicle was operated over the selected test cycle. This preliminary test run also provided a suitable time for the vehicle to reach normal operating temperature prior to the actual test sequence.

In addition to demonstrating the effectiveness of diesel emission control devices this program also involved the evaluation of various cleaner burning diesel fuels. Baseline emission tests were performed using a low sulfur diesel fuel (300 to 500 ppm), typically used in City of Houston vehicles. Upon completion of the baseline tests the vehicle fuel tank was drained and new fuel filters installed. The vehicle was then filled with ¼ tank of the diesel-water emulsion fuel and operated for fifteen minutes. The fuel was then drained and again filled with ¼ tank of the diesel-water emulsion fuel and the engine operated for fifteen minutes. This procedure was then repeated a third time and the tank filled to half capacity in order to perform the emission test sequence.

In order to demonstrate the effectiveness of diesel emission control devices to reduce exhaust emissions, several manufacturers provided various technologies for evaluation. The manufacturer of the technology installed each device on selected diesel-powered equipment. After installation, the vehicle was returned to regular service for a period of time, deemed appropriate by the manufacturer, in order to degreen the technology. At the conclusion of this time period subsequent emissions testing was completed with the technology installed.

3.1 Dynamic Dilution Of/Off-Road Exhaust Emissions Sampling System (DOES2™)

The DOES2 is a compact, self-contained transportable instrument that facilitates the on-board, in-use testing of a vehicle's exhaust stream emissions. The DOES2 technology can be used for emissions characterization, emission control technology evaluations, assessment of alternate fuels and technologies, and vehicle maintenance. It can be applied to emissions testing of a variety of mobile sources from light to heavy-duty configurations for conventional, off-road on non-road vehicles in land, marine, and aviation applications. The technology is particularly effective in producing repeatable and accurate measurements in field applications that would normally be performed in the controlled setting of an emissions measurement laboratory using conventional laboratory equipment such as a chassis dynamometer.

The DOES2 technology was developed at the Emissions Research and Measurement Division of Environment Canada. The technology has participated in a number of collaborative emissions projects with government departments (Canada, the United States, China and Colombia), agencies (Northeast States for Coordinated Air Use Management, NESCAUM), and private companies involving emissions evaluation and alternate fuel development.

3.2 Test Vehicles

A large cross-section of diesel fueled vehicles, Figure 4, were selected for this evaluation program and were provided by various City of Houston Departments; Fire, Public Works, Solid Waste, Parks & Recreation. A detailed description of the test vehicles is presented in Table 1.

Figure 4 Various City of Houston Demonstration Program Test Vehicles

Table 1 City of Houston Test Vehicle Fleet Description

UNIT #	YEAR	EQUIPMENT TYPE	MANUFACTURER	SIZE OF ENGINE	TECHNOLOGY
18898	1992	International 4600 4X2 Flatbed	International	7.3L	Lubrizol
20023	1992	Gradall G3WD	Cummins	6BTA 5.9L 190 hp	Lubrizol - ECS
20027	1992	Gradall G3WD	Cummins	6BTA 5.9L 190 hp	Lubrizol - Ceryx
20031	1992	Gradall G3WD	Cummins	6BTA 5.9L 190 hp	Extengine
21003	1993	Ford LTS-9000 Dump Truck 10 cu yd	Cummins	L10 10.0L 280hp	Ceryx
21762	1993	Tractor Mower	Ford	5.0 L 76HP	Lubrizol - ECS
23026	1994	Gradall G3WD	Cummins	6BTA 5.9L 190 hp	Ceryx
23027	1994	Gradall G3WD	Cummins	6BTA 5.9L 190 hp	Johnson-Mathey
23555	1995	International 4700 Dump Truck 5 cu yd	International	T444E 7.3 L 175 HP	Lubrizol
23659	1995	International 4700 Dump Truck 5 cu yd	International	T444E 7.3 L 175 HP	Lubrizol
23686	1995	Ford LTS-9000 HeavyTruck	Cummins	L10 10.0L 280hp	Johnson-Mathey
25140	1996	Road sweeper HD	John Deere	4039T 110HP	Lubrizol
26701	1997	Recycle Split rear loader SW	Detroit Diesel	Series 50 310 HP	Lubrizol - ECS
28029	1998	Heavy Vacuum cleaner	Cummins	M11 330 hp	CITGO
28135	1998	John Deere Mower	John Deere	53 HP Diesel 3 cyl	CleanAIR Systems
28138	1998	Tractor Mower	John Deere	2.9 L 179 CID 45HP	Lubrizol
28320	1998	Pump, Gorman Rup	Duetz	80 HP	CleanAIR Systems
29333	1999	International 4700 Dump Truck 5 cu yd	International	T444E 7.3 L 175 HP	CITGO
29335	1995	International 4700 Medium Truck	International	T444E 7.3 L 175 HP	Johnson-Mathey
29470	1999	Mower, Turf blazer	Yanmar Diesel	32 HP 3 cyl	CleanAIR Systems
29946	1999	Truck, Fire Pumper E-08	Detroit Diesel	Series 60 12.7 L 370hp	Ceryx
29997	1999	Truck, Fire Pumper E-07	Detroit Diesel	Series 60 12.7 L 370hp	Siemens-Westinghouse
30298	1999	Automated Sideloader SW	Volvo Diesel	VE 275 HP	Engelhard
30390	1999	Chevrolet CC31003	General Motors	6.5 Turbo Diesel	Ceryx
30453	1999	Backhoe	Ford New Hollan	450T 90HP 276 CID	Lubrizol
30487	1999	Truck, Fire Pumper E-48	Detroit Diesel	Series 60 12.7 L 370hp	Johnson-Mathey
30490	2000	Heavy Vacuum cleaner	Cummins	ISMU+ 305HP	Engelhard
30491	2000	Heavy Vacuum cleaner	Cummins	ISMU+ 305HP	Siemens-Westinghouse
30535	1999	John Deere Mower	John Deere	53 HP Diesel 3 cyl	CITGO
30661	2000	Excuvator	Yanmar Diesel	12 HP	CleanAIR Systems
30662	2000	Excuvator	Yanmar Diesel	12 HP	CleanAIR Systems
31045	2000	Chevrolet CC31003	General Motors	6.5 Turbo Diesel	CITGO
G100025	1999	Hustler Shortcut Mower	Kohler Diesel	20 HP 2 cyl	CleanAIR Systems
Int. Truck	2000	International Dump Truck 10 cu yd	International	ISMU+ 370HP	CITGO

3.3 Baseline Test Fuel

The test fuel used during the baseline emissions evaluation was commercial diesel fuel (300 to 500 ppm) purchased by the City of Houston for use by their on site fleet. Average fuel properties of the baseline diesel fuel are summarized in Table 2.

Table 2 Baseline Diesel Fuel Properties

Parameter	Method	Result
Density @ 15^o C	ASTM D-4052	853.3
Sulfur % Weight	ASTM D-4294	< 0.05
Ash % Weight	ASTM D-482	< 0.001
Water % by Distillation	ASTM D-86	<0.05
Cetane Index	ISO 4262	46.0
Net Calorific Value (mg/kg)	Calculated	139,568

3.4 Test Cycles

The test cycles used for emissions testing in this project were specifically developed to be representative of the vehicle's characteristic daily in-use operation. In order to characterize the in-use operations of each vehicle a detailed daily activity chart was provided by the appropriate City of Houston Department. This information included vehicle task, engine operating parameters, and time of operation. Six test cycles were identified for this study:

Cycle A – Fire Truck Cycle
Cycle B – Garbage Truck Cycle
Cycle M – Field Mower Cycle
Cycle O – On-Road Cycle
Cycle S – Steady-State Operation Cycle
Cycle T – Off-Road Excavation Cycle

These test cycles were developed to be representative of the vehicle operation and to enhance the repeatability of the testing by the operator. This repeatability was essential in order to attribute any emission differences to the exhaust emission control device or cleaner burning diesel fuel, and not the test cycle. As a result, tests completed using the mobile emissions sampling system (DOES2), were conducted over conditions that reflected the normal operation of the engine/equipment as per Retrofit Technology In-Use Testing Requirements under the USEPA Voluntary Diesel Retrofit Program.

Fire Truck Cycle - The Fire Truck Cycle consisted of a typical urban driving sequence, achieving speeds of 30 miles per hour. A three-minute high idle sequence and then a two-minute pumping sequence followed the driving mode. The Fire truck was then driven back to the starting point. This cycle was 1.733 miles in total distance.

Figure 5 Typical Fire Truck Cycle Engine Air Intake Profile

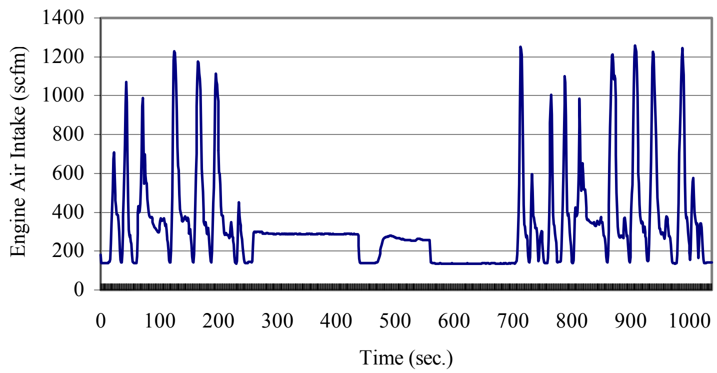


Figure 6 Typical Fire Truck Cycle Exhaust Temperature Profile

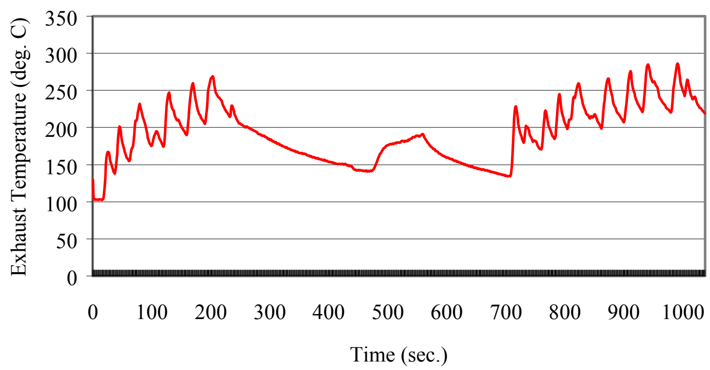
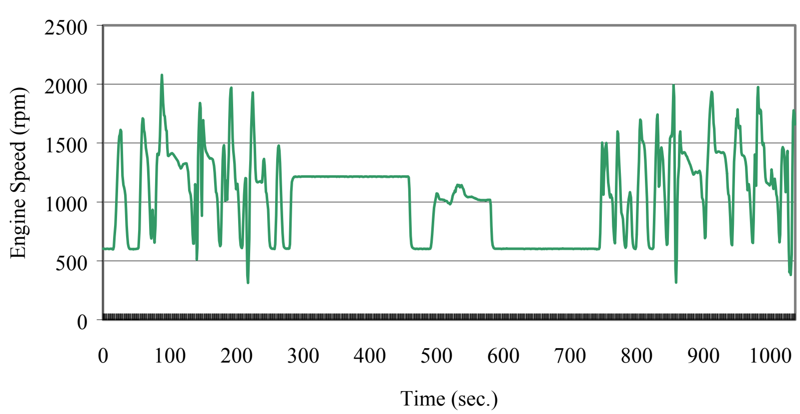


Figure 7 Typical Fire Truck Cycle Engine Speed Profile



Garbage Truck Cycle – The Garbage Truck Cycle was comprised of a 32 start and stop sequence with heavy accelerations and decelerations characteristic of its daily use. This cycle was 3.778 miles in total distance.

Figure 8 Typical Garbage Truck Cycle Engine Air Intake Profile

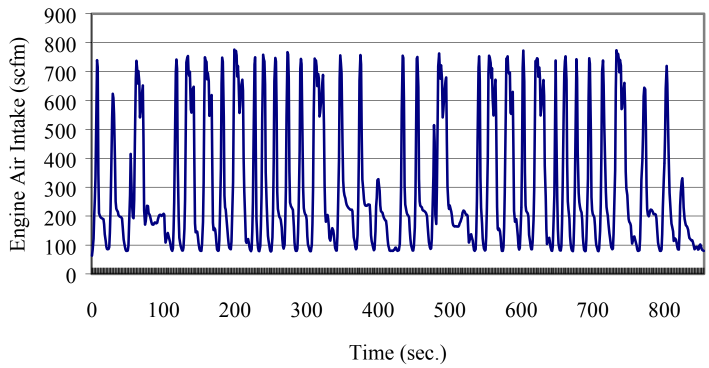


Figure 9 Typical Garbage Truck Cycle Exhaust Temperature Profile

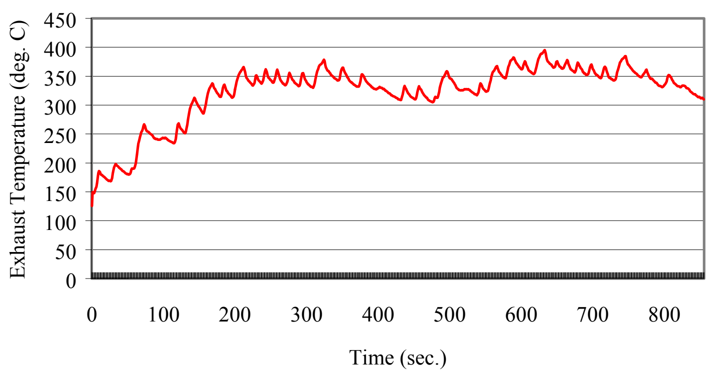
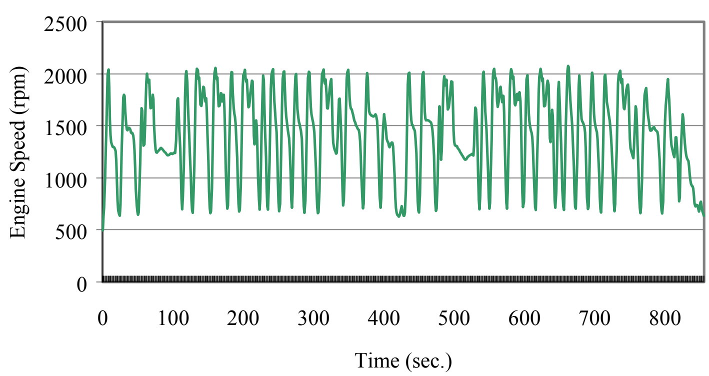


Figure 10 Typical Garbage Truck Cycle Engine Speed Profile



Field Mower Cycle – The Field Mower Cycle consisted of a short drive from the starting point to a large field area, followed by a continuous mowing sequence, and then a short drive back to the starting point. This cycle was 0.829 miles in total distance.

Figure 11 Typical Field Mower Cycle Engine Air Intake Profile

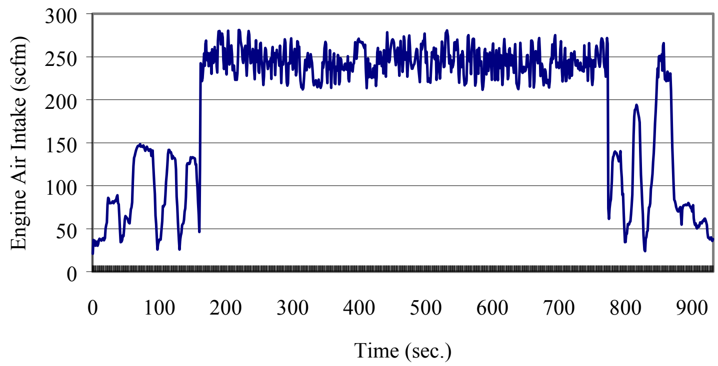


Figure 12 Typical Field Mower Cycle Exhaust Temperature Profile

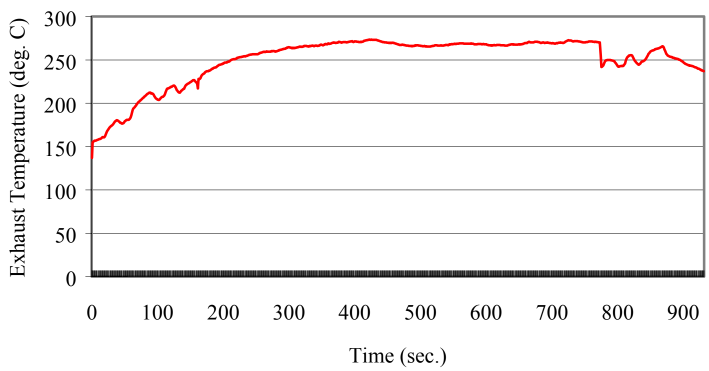
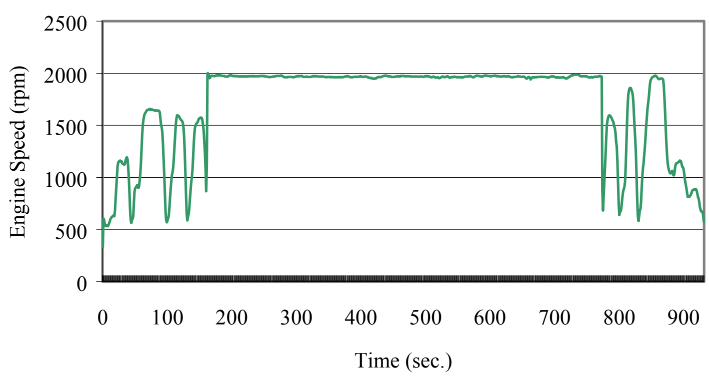


Figure 13 Typical Field Mower Cycle Engine Speed Profile



On-Road Cycle – The On-Road Driving Cycle was comprised of a typical urban driving sequence, with numerous accelerations and decelerations. This cycle was 4.470 miles in total distance.

Figure 14 Typical On-Road Cycle Engine Air Intake Profile

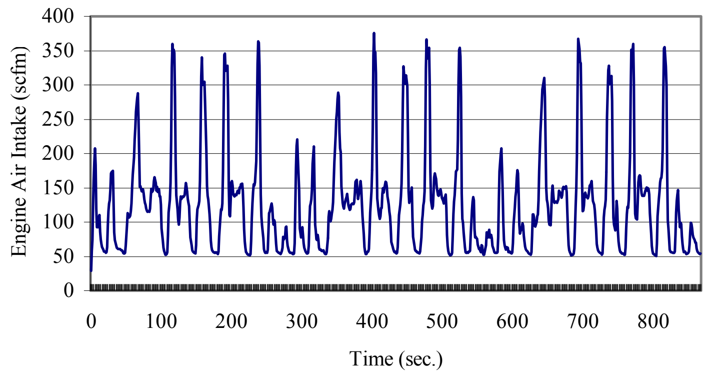


Figure 15 Typical On-Road Cycle Exhaust Temperature Profile

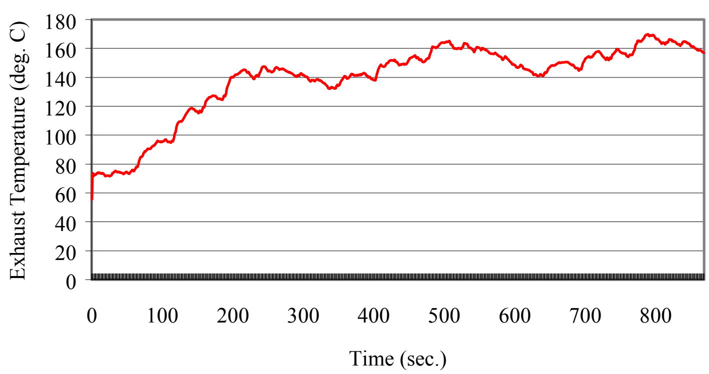
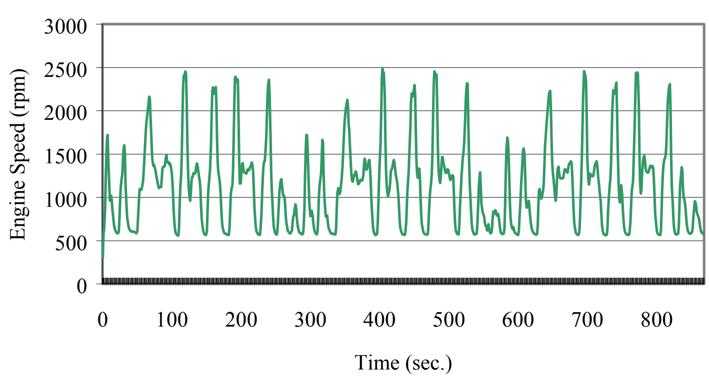


Figure 16 Typical On-Road Cycle Exhaust Temperature Profile



Steady State Cycle – The Steady State Cycle was simply a constant operation used for the Gorman-Rup pump only. This was a stationary pump used for pumping water at a constant flow rate.

Figure 17 Typical Steady State Cycle Engine Air Intake Profile

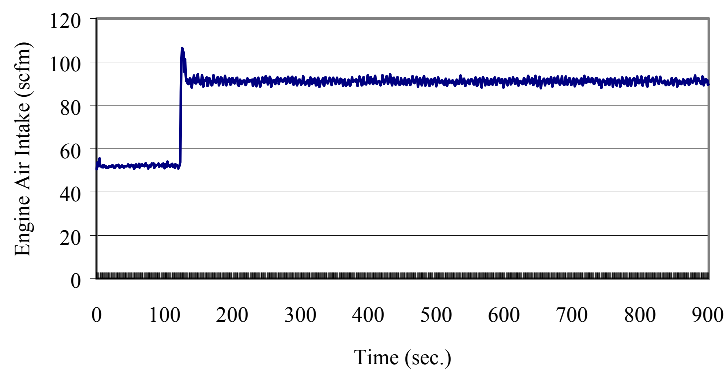


Figure 18 Typical Steady State Cycle Exhaust Temperature Profile

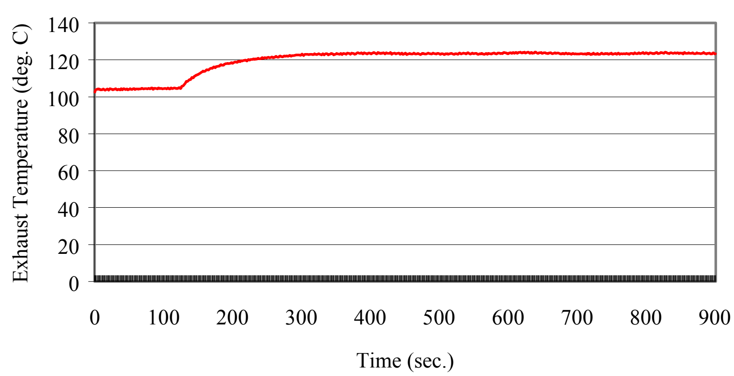
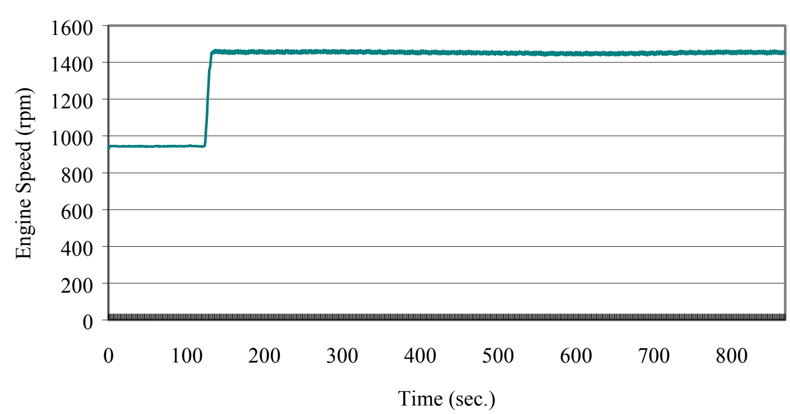


Figure 19 Typical Steady State Cycle Engine Speed Profile



Off-Road Excavation Cycle – The Off-Road Excavation Cycle included a short urban driving sequence, followed by an excavation cycle. This cycle was 1.126 miles in total distance.

Figure 20 Typical Off-Road Excavation Cycle Engine Air Intake Profile

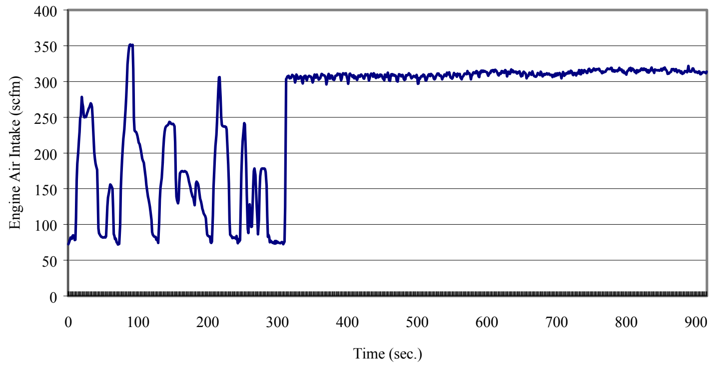


Figure 21 Typical Off-Road Excavation Cycle Exhaust Temperature Profile

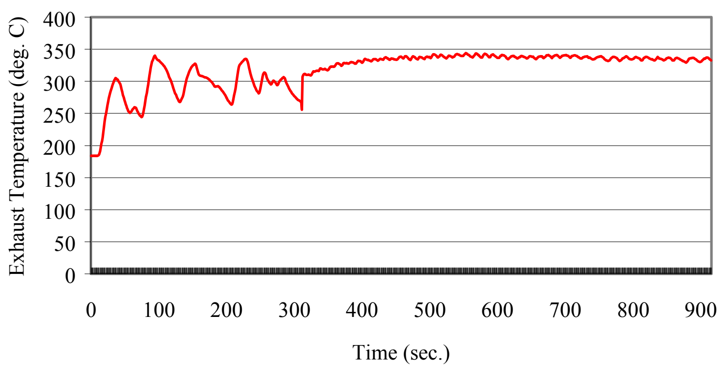
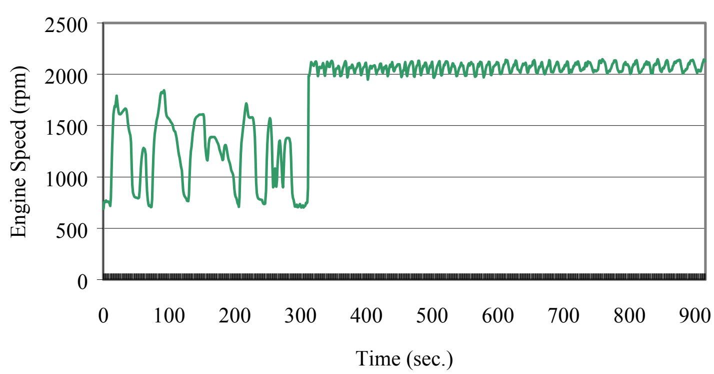


Figure 22 Typical Off-Road Excavation Cycle Engine Speed Profile



4.0 SAMPLING REQUIREMENTS

In order to provide in-use emission characterization of the test vehicles, Environment Canada utilized a unique exhaust emission sampling system, DOES2^{TM}. This allowed for the collection of gaseous and particulate emissions while the vehicles were operated under normal operating conditions. This equipment is a heated, self-contained automated sampling system, which was developed to be mounted onto the vehicle, Figure 23. This computer controlled sampling system extracted a proportional sample of the total vehicle exhaust using a heated sample line and transferred this sample to a mini-dilution tunnel. The raw exhaust was then mixed with ambient air to prevent the condensation of water in the sample and to dilute the concentration of the sample for analysis. The amount of raw exhaust entering the dilution tunnel was varied dependant on the exhaust flow rate of the engine. Measuring the airflow into the engine and using this value to automatically control the amount of dilution air, achieved the proportional sampling. At the outlet of the dilution tunnel, a 70 mm diameter Teflon coated glass fiber filter captured total particulate matter. Upstream of the filter holder, a sample probe was installed in the dilution tunnel in order to extract a gaseous sample into a Tedlar sample bag for analysis. This gaseous sample was analyzed on site by a heated flame ionization detector for hydrocarbons (HC), a heated chemiluminescence detector for oxides of nitrogen (NOx), and non-dispersive infrared detectors for carbon monoxide (CO) and carbon dioxide (CO_2). The entire sampling system underwent routine daily quality assurance and calibration as per Emissions Research and Measurement Division / Environment Canada Federal Test Requirements.

Figure 23 Environment Canada Automated Mobile Sampling System (DOES2^{TM})

5.0 VEHICLE INSTRUMENTATION

Each test vehicle underwent a non-intrusive installation of the sampling equipment and various sensors in order to measure vehicle and engine parameters such as, engine speed, exhaust temperature and engine air intake.

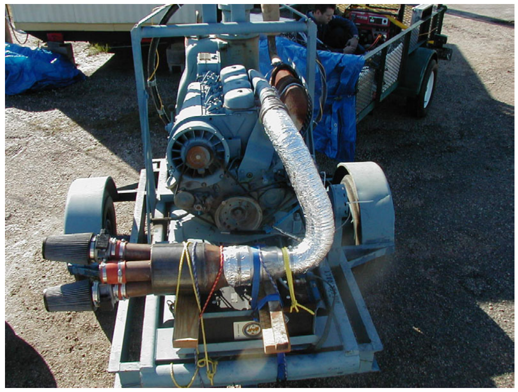
Speed Pick-Up – The engine speed was measured using a magnet and a Hall Effect Sensor. The magnet was glued onto the crankshaft pulley and the Hall Effect Sensor secured in place. The pulse train from the sensor was fed into a frequency to voltage converter chip in the sampling system and the computer read the corresponding voltage.

Exhaust Temperature – The exhaust temperature was measured using a K-type thermocouple, installed in the exhaust stream approximately three inches from the exhaust sample probe.

Figure 24 Exhaust Temperature Thermocouple and Sample Probe

Engine Air Intake – Engine air intake was measured using a multiple of hot wire anemometers. The number of anemometers used for air intake measurement was dependent upon the test vehicle's engine size. As well, the inlet air density to the elements was determined by measuring the absolute pressure and temperature. When the vehicle was at normal operating temperature and idle, an initial intake airflow measurement was made. As the vehicle accelerated and the air intake increased, the ratio of the actual value to the idle value was calculated and used to control the amount of dilution air pumped into the dilution tunnel to allow for a proportional sample.

Figure 25 Engine Air Intake Anemometers



6.0 RESULTS

A summary of the average regulated gaseous and particulate emissions of each emission reduction technology is presented in the following section.

6.1 Ceryx Incorporated

The Ceryx emission reduction technology incorporated simultaneous oxidation and reduction with controlled hydrocarbon injection. The concept employs a non-precious-metal based lean NOx catalyst with supplementary fuel injection. The fuel acts as the reducing agent for the catalyst as well a source of energy to elevate the catalyst temperature for optimum performance.

The vehicles tested using Ceryx technology had engine horsepower ratings of 190 hp to 280 hp. The various test configurations are outlined in Table 3, together with a summary of the averaged emission results.

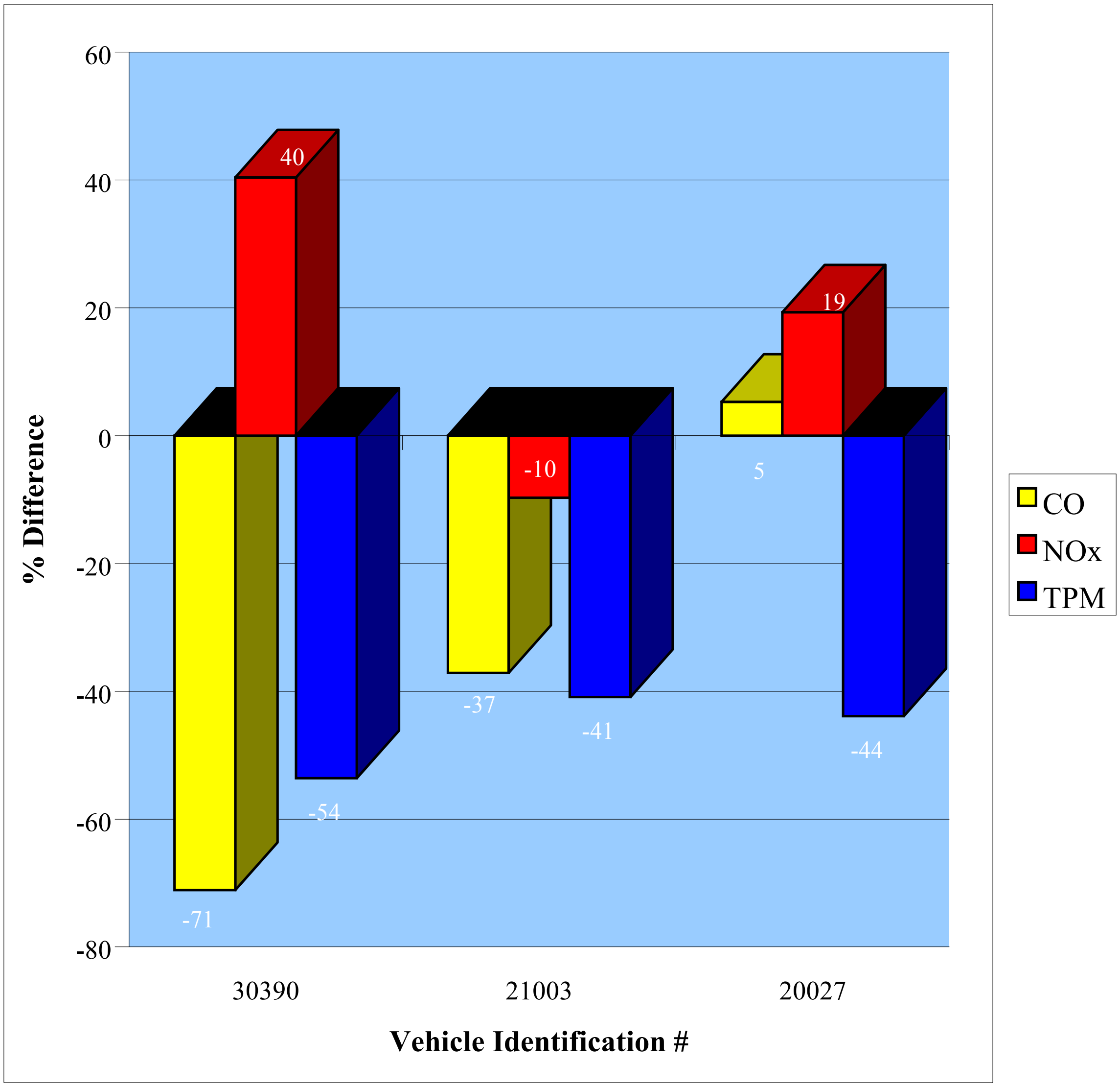
Baseline emission tests were first performed on the five Ceryx equipped vehicles. Vehicles # 30390 and # 21003 tested the Ceryx device installed and using City of Houston baseline diesel fuel. Gradall # 20027 was tested with the Ceryx device and using Lubrizol PuriNOx water/emulsion fuel. Fire truck E-08 # 29946 was tested in baseline configuration and then removed from the program.

Table 3 Result Summary of Ceryx Equipped Vehicles (grams/minute)

Vehicle ID	Vehicle	Configuration	CO	CO_2	NOx	HC	TPM
30390	Chevrolet CC31003 Pickup	Baseline	0.49	287	1.64	0.02	0.042
		Ceryx Installed	0.14	347	2.30	0.56	0.019
21003	FORD LTS-9000 Dump Truck	Baseline	1.96	834	7.41	0.46	1.026
		Ceryx Installed	1.23	946	6.70	1.02	0.606
20027	Gradall G3WD	Baseline	1.48	795	3.41	0.18	0.255
		Ceryx + PuriNOx	1.56	819	4.07	1.28	0.143
29946	Fire Pumper Truck E-08	Baseline	1.23	696	7.73	0.05	0.126
		Ceryx	N/A	N/A	N/A	N/A	N/A

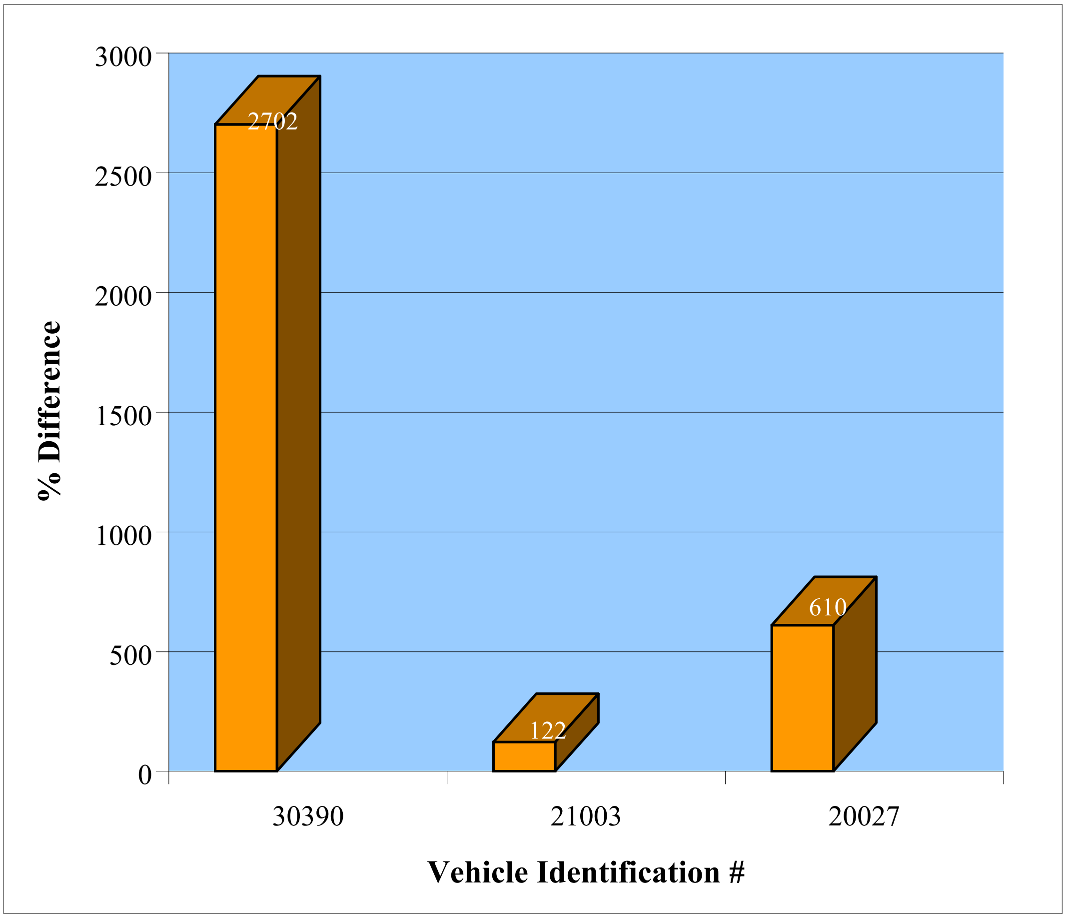
Of the three vehicles only the FORD LTS-9000 Dump Truck # 21003, exhibited a reduction in NOx emissions, up to 10 %. An increase in NOx emissions of 19 % was observed with Gradall # 20027 and 40 % with Chevrolet CC31003 Truck # 30390. Total particulate matter emissions of the three vehicles were reduced by 41 % to 54 % with the Ceryx device installed. Two vehicles had CO emission reductions of up to 71 % with the Ceryx device installed, while the third vehicle demonstrated a slight increase of 5 %. The effect of the Ceryx technology on CO, NOx and TPM is presented in Figure 26.

Figure 26 The Effect Of Ceryx Emission Reduction Technology on CO/NOx/TPM



HC emission rates for all test vehicles utilizing the Ceryx technology increased by up to 28 times in comparison to baseline configuration, Figure 27. This is attributed to the supplementary fuel injection necessary for the reduction catalyst. Clearly the excess fuel was being emitted as raw fuel or as partial combustion by-products.

Figure 27 The Effect of Ceryx Emission Reduction Technology on HC Emissions



6.2 CleanAIR Systems Incorporated

The CleanAIR Systems' catalyzed particulate filter emission reduction technology is designed to oxidize gaseous exhaust emission components and reduce particulate by converting the soot into carbon dioxide and water vapor.

Six vehicles were tested utilizing the CleanAIR Systems technology, with an engine horsepower range of 12 to 80. The effects on the exhaust emissions of the CleanAIR equipped vehicles are presented in Table 4.

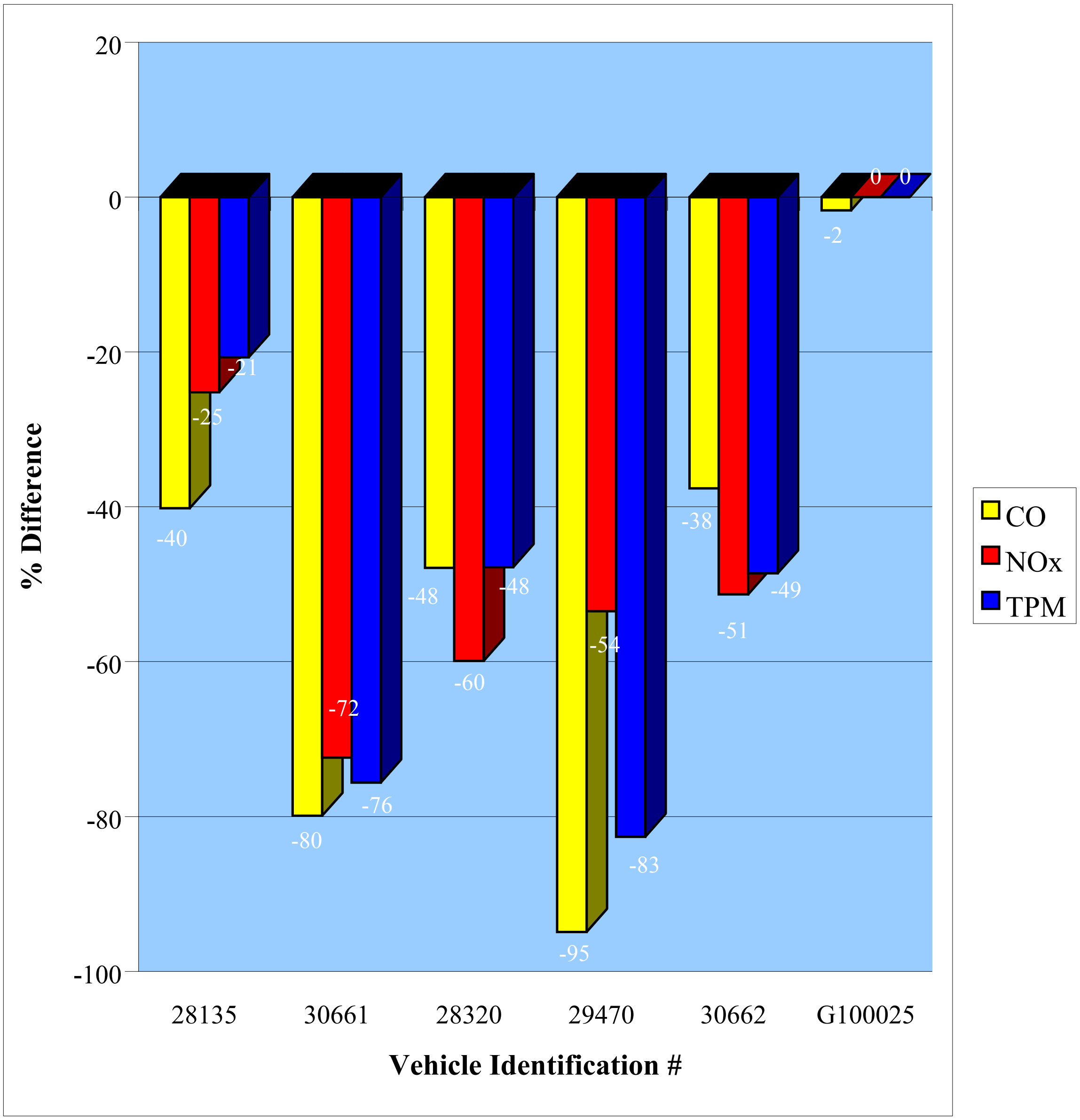
Table 4 Result Summary of CleanAIR Systems Equipped Vehicles (grams/minute)

Vehicle ID	Vehicle	Configuration	CO	CO_2	NOx	HC	TPM
28135	John Deere Mower	Baseline	3.37	436	5.78	0.41	0.519
		CleanAIR Systems	2.01	426	4.33	0.23	0.412
30661	Yanmar Excavator	Baseline	2.33	395	1.53	0.71	0.425
		CleanAIR Systems	0.47	402	0.42	0.36	0.104
28320	Gorman Rup Pump	Baseline	1.89	71	0.84	0.38	0.373
		CleanAIR Systems	0.98	76	0.34	0.39	0.195
29470	Turf Blazer Mower	Baseline	5.06	636	3.53	1.80	0.755
		CleanAIR Systems	0.26	652	1.64	0.20	0.132
30662	Yanmar Excavator	Baseline	0.63	146	0.76	0.10	0.035
		CleanAIR Systems	0.39	149	0.37	0.07	0.018
G100025	Hustler Shortcut Mower (Gasoline)	Baseline	2.78	27	0.06	0.10	N/A
		CleanAIR Systems	2.73	26	0.06	0.10	N/A

The CleanAIR Systems technology was installed on five diesel-fueled vehicles and one gasoline-fueled vehicle. The diesel-fueled vehicles exhibited NOx emissions reductions between 25 % and 72 % when equipped with the CleanAIR system in comparison to the baseline configuration. Total particulate emissions were reduced between 21 % and 83 % by the CleanAIR system. CO emissions were reduced up to 95 %. The CleanAIR system had minimal impact on the fuel consumption of the vehicles, as the CO2 values were essentially the same for tests conducted with and without the technology installed.

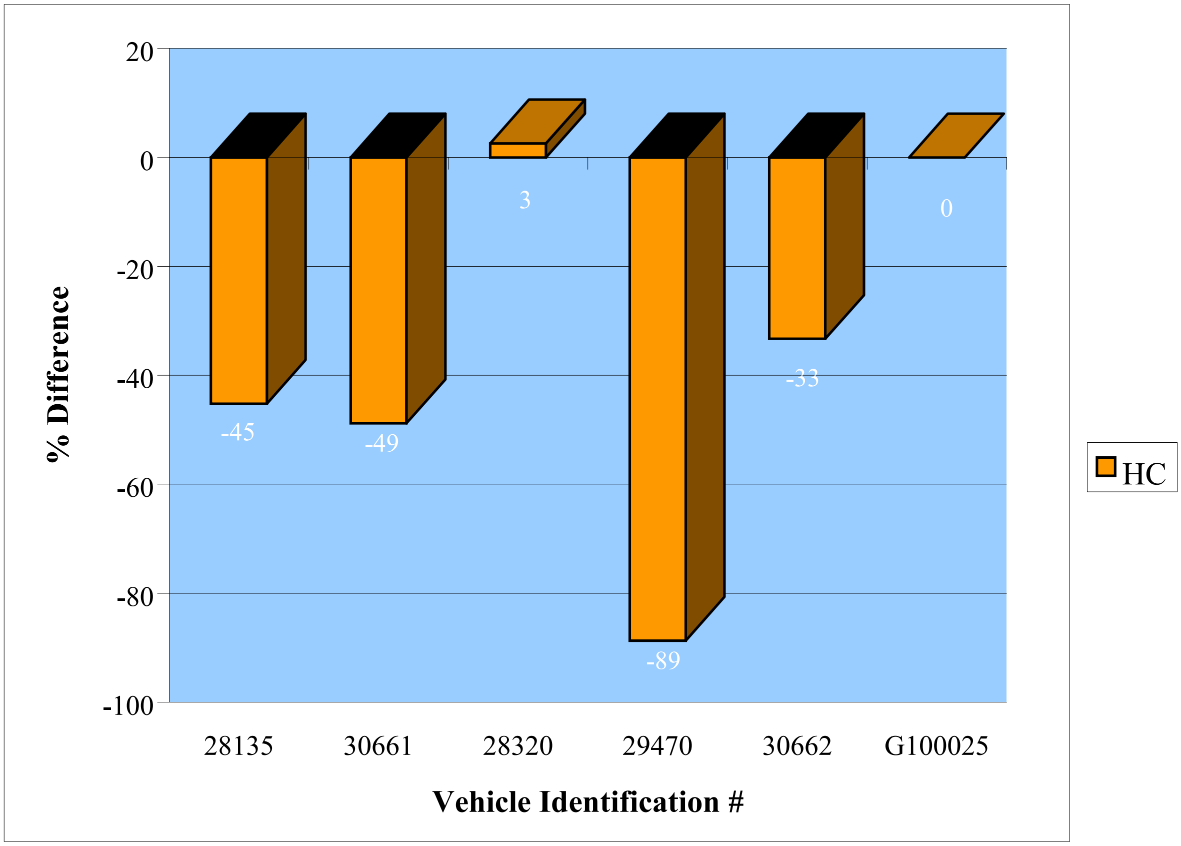
Vehicle # G100025 was a gasoline-fueled mower. The CleanAIR Systems technology exhibited a reduction of less than 2 % in CO emissions on this vehicle.

Figure 28 The Effect of CleanAIR Systems Emission Reduction Technology on CO/NOx/TPM/HC



The device did not yield a statistically significant effect on the gasoline-fueled mower's NOx, HC or TPM emissions. The effect of CleanAIR systems technology on CO, NOx, HC and TPM is presented in Figure 28.

Figure 29 The Effect Of CleanAIR Systems Emission Reduction Technology on HC



6.3 Lubrizol PuriNOx Fuel

The PuriNOx fuel is comprised of the PuriNOx additive package, purified water and diesel fuel. The components are mixed in an electronically controlled, automated blending unit to produce a stable, finished fuel. The primary objective of the technology is to reduce the emission rates of NOx by minimizing the elevated temperature zones in the cylinder during combustion.

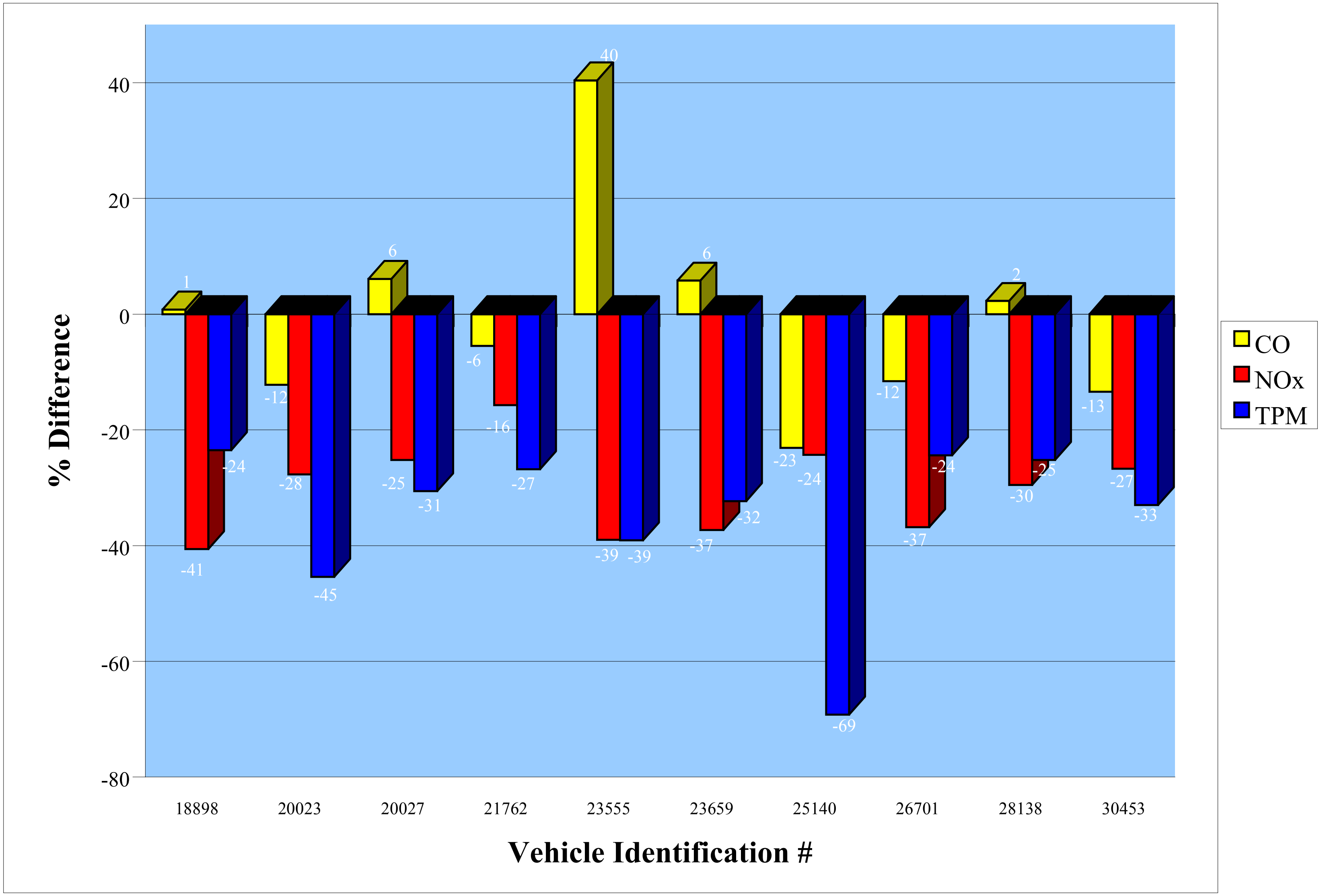
Ten vehicles were tested utilizing the Lubrizol PuriNOx Performance Systems technology with an engine horsepower range of 45 to 310.

Vehicles operating on PuriNOx exhibited NOx reductions from 16 % to 41 %. The International Flatbed 4600, vehicle #18898 exhibited the largest reduction in NOx emissions when operated on PuriNOx in comparison to baseline diesel operation. Total particulate emissions were reduced by 24 % to 69 % when the vehicles were operated with PuriNOx in comparison to baseline diesel operation. A summary of the emission measurements obtained using the baseline diesel fuel and Lubrizol PuriNOx are presented in Table 5. The effect on CO, NOx and TPM emissions of the vehicles utilizing PuriNOx is presented in Figure 30.

Table 5 Result Summary of Lubrizol PuriNOx Fueled Vehicles (grams/minute)

Vehicle ID	Vehicle	Configuration	CO	CO_2	NOx	HC	TPM
18898	International 4600 4X2 Flatbed	Baseline	4.82	534	2.44	0.94	0.166
		PuriNOx	4.86	579	1.45	0.98	0.127
20023	Gradall G3WD	Baseline	1.31	873	6.61	0.27	0.527
		PuriNOx	1.15	996	4.78	0.22	0.288
20027	Gradall G3WD	Baseline	1.48	795	3.41	0.18	0.255
		PuriNOx	1.57	815	2.55	0.16	0.177
21762	Ford Tractor Mower	Baseline	1.28	317	3.06	0.14	0.514
		PuriNOx	1.21	325	2.58	0.18	0.376
23555	International 4700 Dump Truck	Baseline	1.04	444	4.39	0.27	0.092
		PuriNOx	1.46	519	2.68	0.35	0.056
23659	International 4700 Dump Truck	Baseline	1.21	334	4.16	0.10	0.065
		PuriNOx	1.28	349	2.61	0.15	0.044
25140	Road Sweeper	Baseline	1.08	387	2.35	0.18	0.532
		PuriNOx	0.83	306	1.78	0.14	0.164
26701	Recycle Split Rear Loader	Baseline	10.33	1471	21.45	0.15	2.066
		PuriNOx	9.13	1581	13.55	0.11	1.562
28138	John Deere Tractor Mower	Baseline	3.45	338	4.57	0.24	0.274
		PuriNOx	3.53	336	3.22	0.30	0.205
30453	Ford New Holland Backhoe	Baseline	0.82	482	2.62	0.05	0.097
		PuriNOx	0.71	545	1.92	0.06	0.065

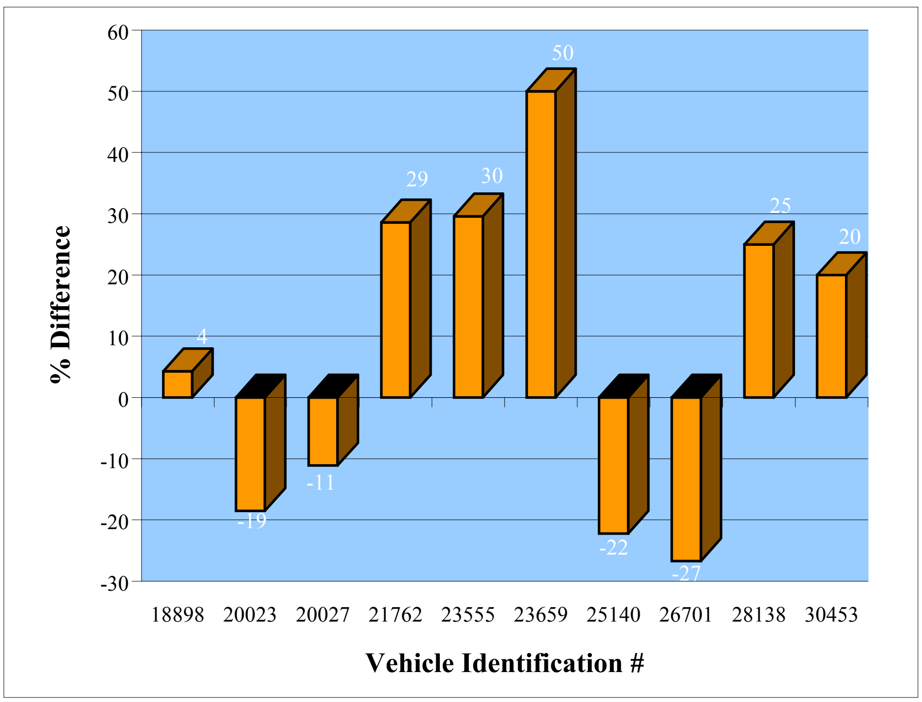
Figure 30 The Effect of Lubrizol PuriNOx on CO/NOx/TPM



Carbon dioxide emissions increased for 8 of the 10 vehicles tested using PuriNOx in comparison to baseline diesel. The water content of the fuel reduces the available energy or total horsepower of the engine. In order to accomplish the same task as with the baseline fuel, the vehicle would have to consume more fuel, as indicated by the increase in CO2 emissions.

The PuriNOx appeared to have a statistically significant effect on HC emissions of the vehicles in comparison to baseline diesel operation. HC emissions for a variety of the vehicles increased by as much as 50 % while other vehicles exhibited a decrease in HC emissions up to 27 %. It should be noted that the hydrocarbon emissions from diesel vehicles are typically low and therefore small, yet statistically significant increases will translate into large percentage increases. In this case the author would recommend that analysis or comparison of the technology refer to the actual emissions data. The effect of PuriNOx on HC emissions is presented in Figure 31.

Figure 31 The Effect of Lubrizol PuriNOx on HC Emissions



6.4 Engine Control Systems AZ Purimuffler + Lubrizol PuriNOx Fuel

The AZ Heavy Duty Direct Fit Purimuffler is an integrated diesel oxidation catalytic converter and silencer, designed specifically for each vehicle to replace the original vehicle muffler. The PuriNOx fuel, as described above, is comprised of the PuriNOx additive package, purified water and diesel fuel. The components are mixed in an electronically controlled, automated blending unit to produce a stable, finished fuel.

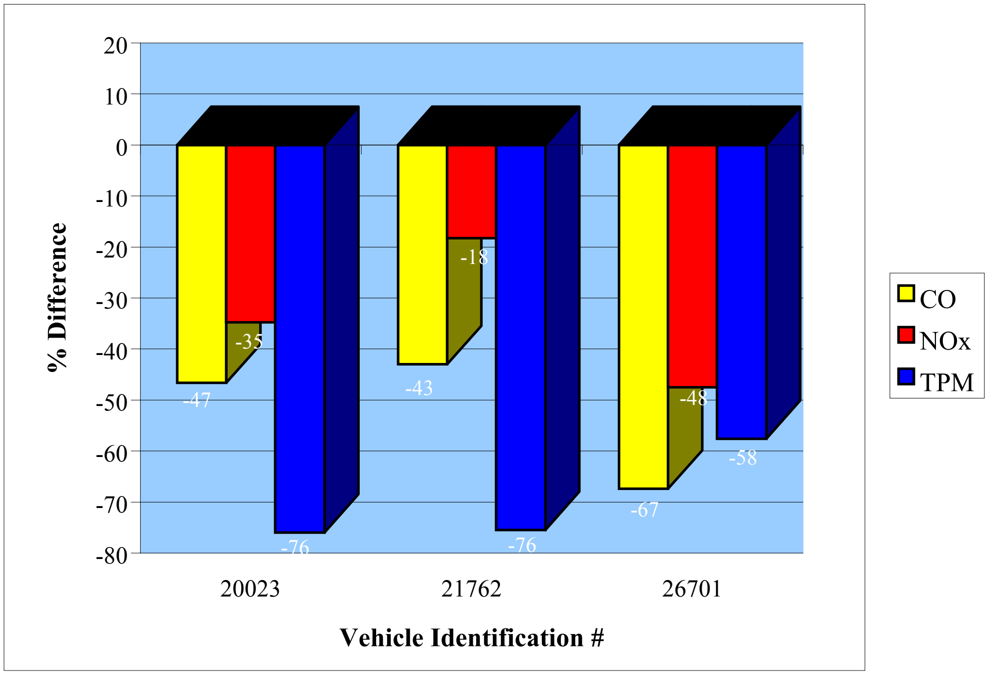
Three vehicles were tested utilizing the AZ Heavy Duty Purimuffler and PuriNOx technology with an engine horsepower range of 76 to 310.
The effects on the exhaust emissions of the vehicles utilizing this technology are presented in Table 6. All three vehicles were tested with baseline diesel followed by PuriNOx without the Engine Control Systems AZ Purimuffler installed followed by PuriNOx with the AZ Purimuffler installed.

The combined effect of the oxidation catalyst and the emulsified fuel resulted in the emission reduction of CO, NOx and TPM. With the AZ Purimuffler / PuriNOx combination, the vehicles exhibited a reduction in CO emissions of up to 67 %, NOx emission reductions of 18 % to 48 %, and TPM emissions were reduced by 58 % to 76 %. A comparison of the emission results obtained with the Engine Control Systems AZ Purimuffler + PuriNOx fuel emission reduction technology and the baseline configuration are presented in Table 6. The effect of Engine Control Systems AZ Purimuffler / PuriNOx on CO, NOx and TPM is presented in Figure 32.

Table 6 Result Summary of AZ Purimuffler Equipped + PuriNOx Fueled Vehicles (grams/minute)

Vehicle ID	Vehicle	Configuration	CO	CO_2	NOx	HC	TPM
20023	Gradall G3WD	Baseline	1.31	873	6.61	0.27	0.527
		PuriNOx	1.15	996	4.78	0.22	0.288
		PuriNOx + Purimuffler	0.70	935	4.31	0.13	0.125
21762	Ford Tractor Mower	Baseline	1.28	317	3.06	0.14	0.514
		PuriNOx	1.21	325	2.58	0.18	0.376
		PuriNOx + Purimuffler	0.73	340	2.50	0.16	0.126
26701	Recycle Split Rear Loader	Baseline	10.33	1471	21.45	0.15	2.066
		PuriNOx	9.13	1581	13.55	0.11	1.562
		PuriNOx + Purimuffler	3.37	1577	11.27	0.08	0.875

Figure 32 The Effect of AZ Purimuffler + PuriNOx on CO/NOx/TPM



6.5 CITGO Diesel Emulsion Fuel

The test fuel was a diesel / water emulsion blended with a proprietary additive package supplied by CITGO Petroleum Corporation.

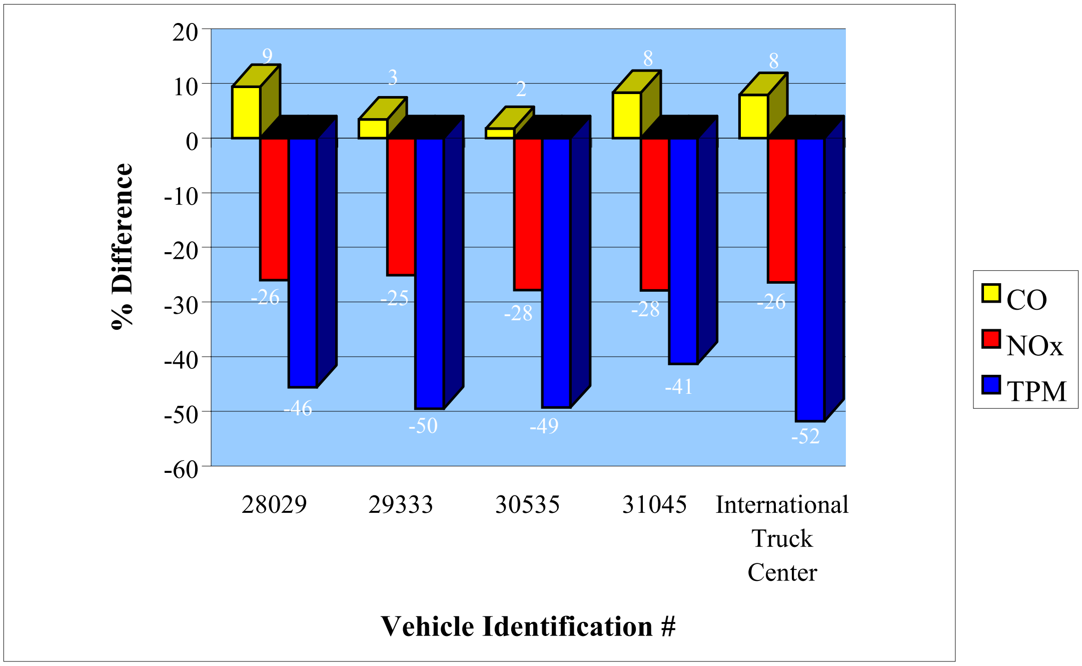
Five different vehicles were operated on the CITGO emulsion fuel with an engine horsepower range of 53 to 370.

In comparison to the baseline fuel, the CITGO emulsion fuel exhibited a decrease in NOx emissions of 25 % to 28 %, and TPM emissions demonstrated a reduction of 41 % to 52 %. Carbon dioxide emissions increased with the CITGO emulsion fuel in comparison to the baseline diesel fuel for all vehicles. This increase reflects the water content of the fuel indicating an increase in fuel consumption. The water content of the fuel reduces the available energy or total horsepower of the engine. In order to accomplish the same task as with the baseline fuel, the vehicle would have to consume more fuel. A comparison of the emission results obtained using the CITGO emulsion fuel and the baseline diesel fuel are presented in Table 7. The effect on the CO, NOx and TPM emissions of the vehicles utilizing the CITGO fuel is presented in Figure 33.

Table 7 Result Summary of CITGO Diesel Emulsion Fueled Vehicles (grams/minute)

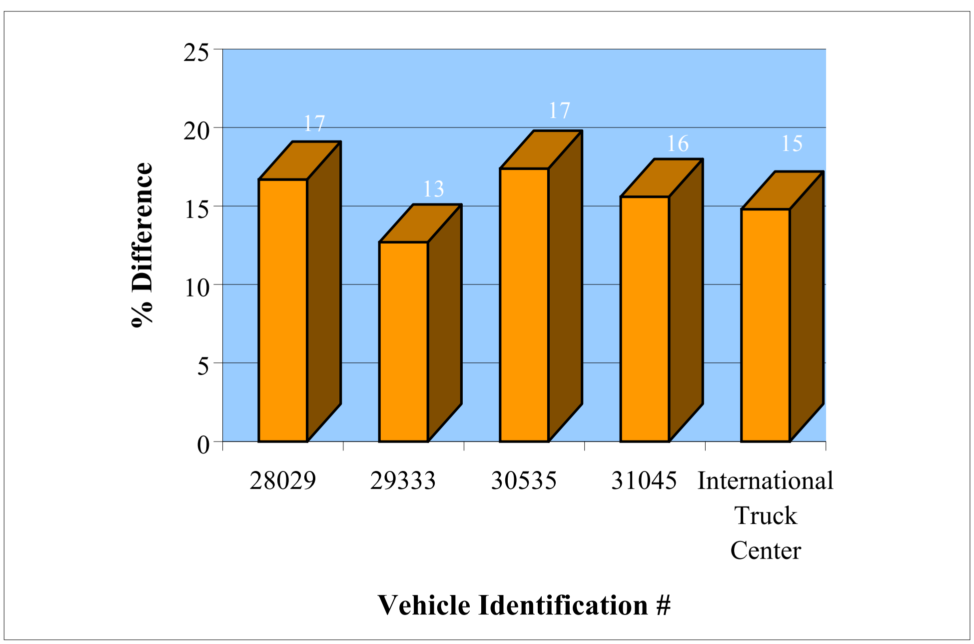
Vehicle ID	Vehicle	Configuration	CO	CO_2	NOx	HC	TPM
28029	Volvo Heavy Vac Truck	Baseline	0.53	846	3.35	0.72	0.114
		CITGO Emulsion	0.58	927	2.48	0.84	0.062
29333	International B175F Dump Truck	Baseline	0.88	435	2.15	0.63	0.093
		CITGO Emulsion	0.91	475	1.61	0.71	0.049
30535	John Deere Tractor Mower	Baseline	3.55	438	3.78	0.46	0.142
		CITGO Emulsion	3.61	495	2.73	0.54	0.072
31045	GM 2500 P/U Truck	Baseline	0.48	275	2.01	0.32	0.046
		CITGO Emulsion	0.52	309	1.45	0.37	0.027
International Truck Center	International 10 cu. yd. Dump Truck	Baseline	3.29	883	2.39	0.27	0.083
		CITGO Emulsion	3.55	933	1.76	0.31	0.040

Figure 33 The Effect of CITGO Diesel Emulsion on CO/NOx/TPM



The hydrocarbon emissions from all CITGO fueled vehicles increased between 13% and 17 % in comparison to baseline diesel tests, Figure 34.

Figure 34 The Effect of CITGO Diesel Emulsion Fuel on HC Emissions



6.6 Engelhard DPX Soot Filter With Complete EGR System

The Engelhard Corporation emission reduction technology incorporated a complete EGR system as well as an Engelhard DPX Soot Filter, which utilizes a wall-flow monolith filter with a proprietary catalyst coating, and Ultra Low-Sulfur diesel fuel (30 ppm Sulfur). The catalyst traps and burns the diesel particulate when exhaust gas temperatures are at a minimum of 375^{o}C for at least 25% of the engine operating time. This technology was used in association with BP Amoco Ultra Low-sulfur diesel (ULSD) fuel.

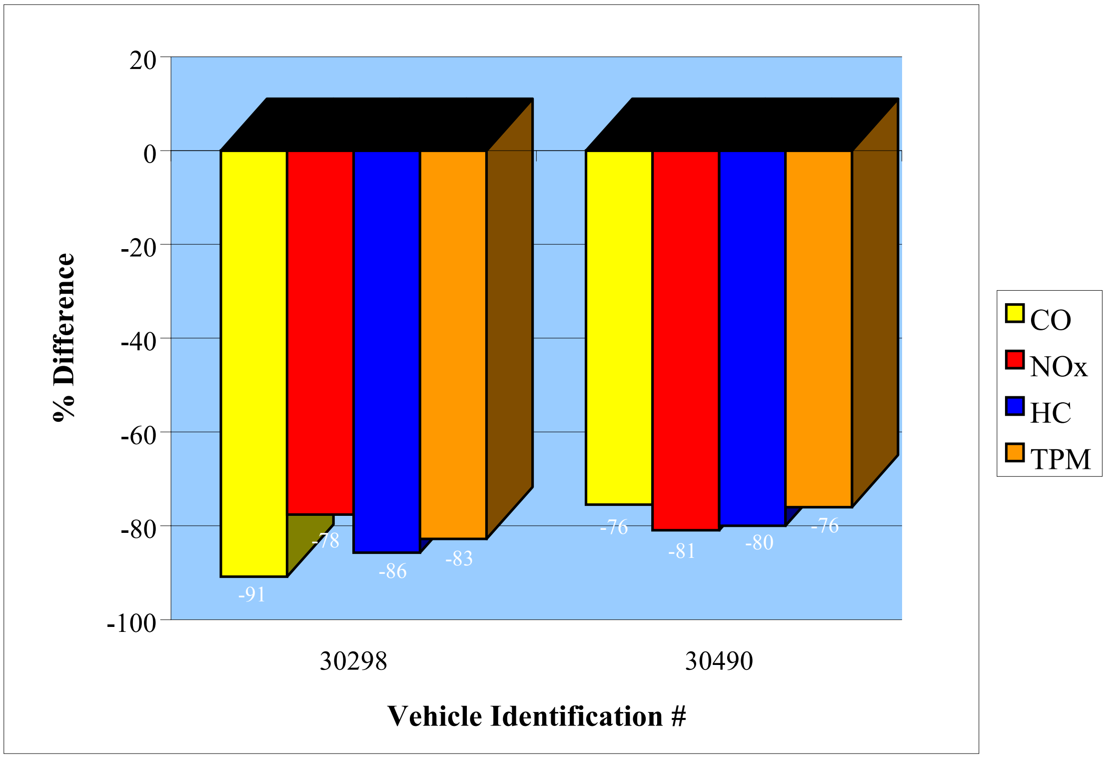
Two different vehicles were operated with the Engelhard DPX Soot Filter and ULSD with an engine horsepower range of 275 to 305.

In comparison to the baseline tests the Engelhard system yielded CO reductions of 76 % to 91 %, NOx emissions were reduced by as much as 81 %, HC emissions were reduced by 80 % to 86 %, and TPM emissions were reduced up to 83 %. A comparison of the emission results obtained with the Engelhard emission reduction technology installed and the baseline configuration are presented in Table 8. The effect on the CO, NOx, HC and TPM emissions of the vehicles utilizing the Engelhard DPX Soot Filter is presented in Figure 35.

Table 8 Result Summary of Engelhard EGR/DPX + ULSD Equipped Vehicles (grams/minute)

Vehicle ID	Vehicle	Configuration	CO	CO_2	NOx	HC	TPM
30298	Automated Side Load Waste Truck	Baseline	1.20	819	4.73	0.07	0.145
		Engelhard EGR/DPX + ULSD	0.11	852	1.06	0.01	0.025
30490	Heavy Vac Cleaner	Baseline	0.98	826	8.48	0.05	0.125
		Engelhard EGR/DPX + ULSD	0.24	825	1.62	0.01	0.030

Figure 35 The Effect of Engelhard EGR/DPX + ULSD on CO/NOx/TPM



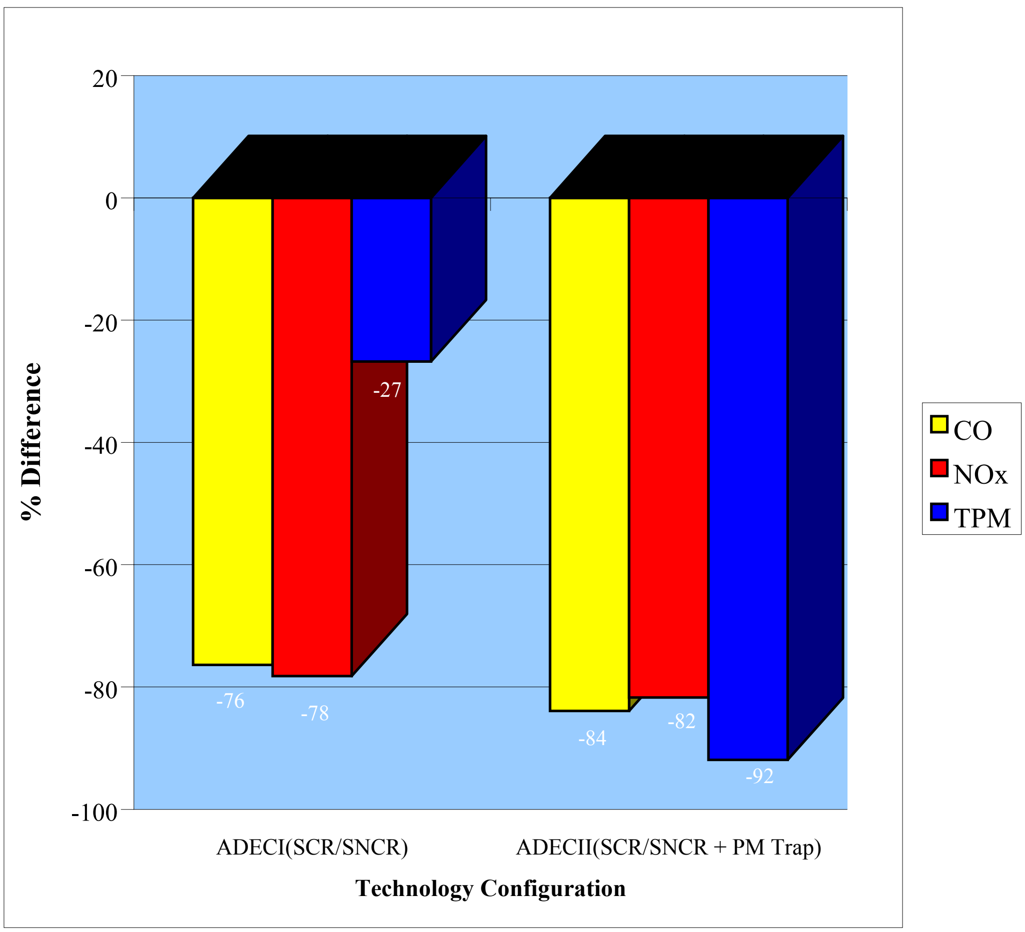
6.7 Extengine ADEC I and ADEC II Diesel Emissions Control System

The Extengine ADEC I (SCR/SNCR) system is based upon the use of ammonia as a reductant diffused at the exhaust manifold (SNCR) and a specially formulated selective catalytic reduction (SCR) component. The ADEC II was comprised of the SCR/SNCR system (ADEC I) in addition to a Particulate Trap using baseline diesel (300 to 500 ppm). The vehicle operated with the Extengine ADEC I and ADEC II systems was a Gradall G3WD with a Cummins 6BTA 5.9 L engine. The ADEC I and ADEC II system produced CO reductions of 76 % to 84 %, while NOx reductions of 78 % to 82 % were also observed. The ADEC I system reduced TPM emissions by 27 % while the ADEC II system reduced TPM by as much as 92 %. A comparison of the emission results obtained with the ADEC I and ADEC II emission reduction technology installed and the baseline configuration are presented in Table 9. The effect on the CO, NOx, and TPM emissions of the vehicles utilizing the ADEC I and ADEC II systems are presented in Figure 36. One of the concerns of SCR systems is the ammonia slip in the exhaust stream after reaction with combustion products. The ammonia slip measured from the Gradall with the ADEC I and ADEC II systems were determined using a MIDAC Fourier Transform Infrared Spectrometer. The concentration of ammonia for all test runs was determined to be <1 ppm.

Table 9 Result Summary of Extengine ADEC I and ADEC II Equipped Vehicles (grams/minute)

Vehicle ID	Vehicle	Configuration	CO	CO_2	NOx	HC	TPM
20031	Gradall G3WD	Baseline	1.06	922	4.91	0.43	0.695
		ADEC I (SCR/SNCR)	0.25	939	1.07	0.15	0.509
		ADEC II (SCR/SNCR + PM trap)	0.17	931	0.90	0.06	0.056

Figure 36 The Effect of Extengine ADEC I and ADEC II on CO/NOx/TPM



6.8 Johnson Matthey SCRT Emission Reduction Technology

The Johnson Matthey SCRT system incorporates a metallic catalyst substrate combined with a urea reducing injection agent and control system using Ultra Low-Sulfur diesel fuel (30 ppm Sulfur). The primary objectives of the system are to reduce the particulate as well as the NOx emissions.

In the initial phase of this program, three City of Houston vehicles underwent baseline emission testing. These vehicles were to be retrofitted with the Johnson Matthey SCRT system. Problems arose with the Johnson Matthey SCRT control system and were not resolved within an adequate time frame in order to complete the emission testing of the device. Subsequent testing is being scheduled for April-June 2002.

6.9 Siemens Westinghouse Power Corporation SINOx SCR Catalyst System

The Siemens Westinghouse Power Corporation SINOx Catalyst System featured a SINOx SCR honeycomb catalyst with urea reducing agent flow control system. The primary objectives of the system are to reduce the particulate as well as the NOx emissions.

Two of the vehicles scheduled for the Siemens Westinghouse system installation underwent baseline emission testing but were removed from the program when the emission reduction technology was not available.

6.10 Long Term Vehicle Emission Variability Component

One of the major concerns brought forward, at the initial City of Houston Diesel Demonstration Advisory Committee meeting, was the amount of time elapsed between initial vehicle baseline emission measurements and measurements made with the emission reduction technology installed or alternate diesel fuel used. In order to address these concerns, vehicle # 23026, a 1994 Gradall with Cummins 6BTA 5.9 L engine was tested in November 2000 and re-tested in March 2001. The results from these tests are presented in Table 10. During this period the vehicle exhibited less than a 5 % deviation in emission measurements made in March in comparison to the initial baseline tests in November. While this represents only a single vehicle from the program it provides some confidence that the interval between testing had no significant impact.

Table 10 Result Summary of Long Term Variability Vehicle (grams/minute)

Vehicle ID	Vehicle	Configuration	CO	CO_2	NOx	HC	TPM
23026	Gradall G3WD	Baseline (Nov.9, 2000)	1.45	1096	6.01	0.23	0.274
		Baseline (Mar.15, 2001)	1.48	1084	6.19	0.23	0.285

6.11 Repeatability and Statistical Variability of Test Cycles and Emission Data

In order to provide a quality control check on the vehicles and the entire emissions sampling system, a minimum of three test cycles were performed for each vehicle-fuel-emission reduction technology combination. Additional tests were performed when the emission result exceeded a pre-determined limit in order to detect result outliers. Exhaust emission repeatability ratios used are presented in Table 11. Additional tests were performed if the higher emission result divided by the lower emission result was greater than the repeatability ratio.

Table 11 Exhaust Emission Result Repeatability Ratios

Exhaust Emission Component	Repeatability Ratio
Carbon Monoxide	1.70
Carbon Dioxide	1.02
Oxides of Nitrogen	1.29
Hydrocarbons	1.33
Total Particulate Matter	1.20

A similar quality control check was utilized to determine test cycle repeatability. Engine air intake, exhaust temperature and engine speed plots were prepared for each test run and summarized for each vehicle-fuel-emission reduction technology combination. A series of three plots were generated for each measured vehicle parameter in order to determine repeatability. Examples of the parameter plots are presented in Figures 37 to 39.

Figure 37 Summary of Engine Intake Air Flow Profiles of 1995 International Dump Truck (ID # 23659) Baseline Diesel Configuration On-Road Cycle

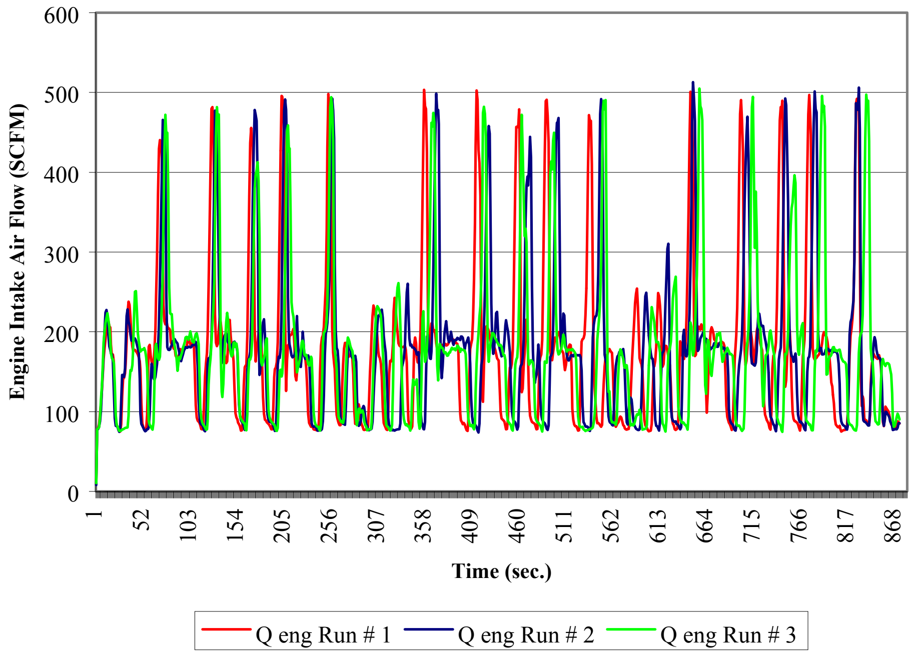


Figure 38 Summary of Exhaust Temperature Profiles of 1995 International Dump Truck (ID # 23659) Baseline Diesel Configuration On-Road Cycle

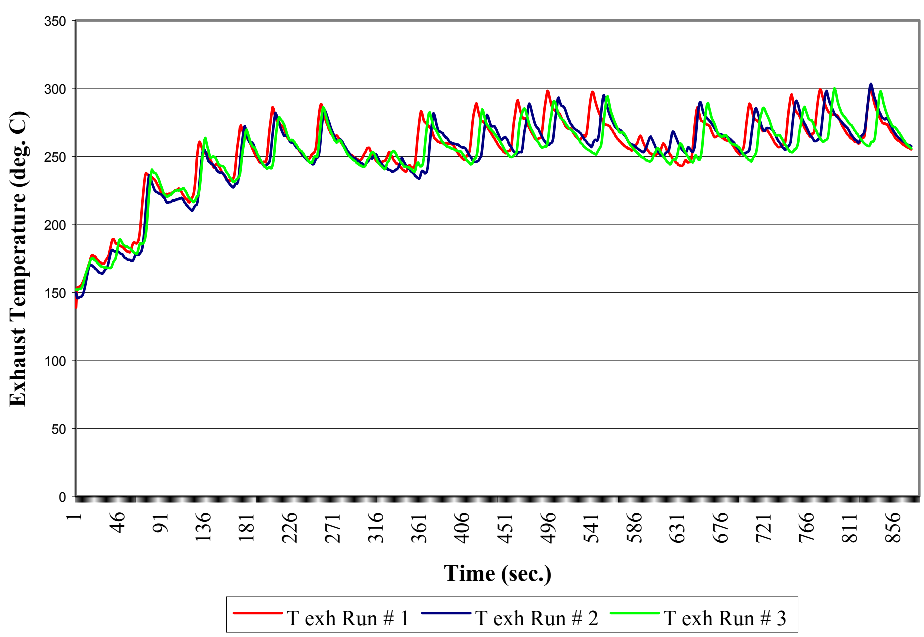
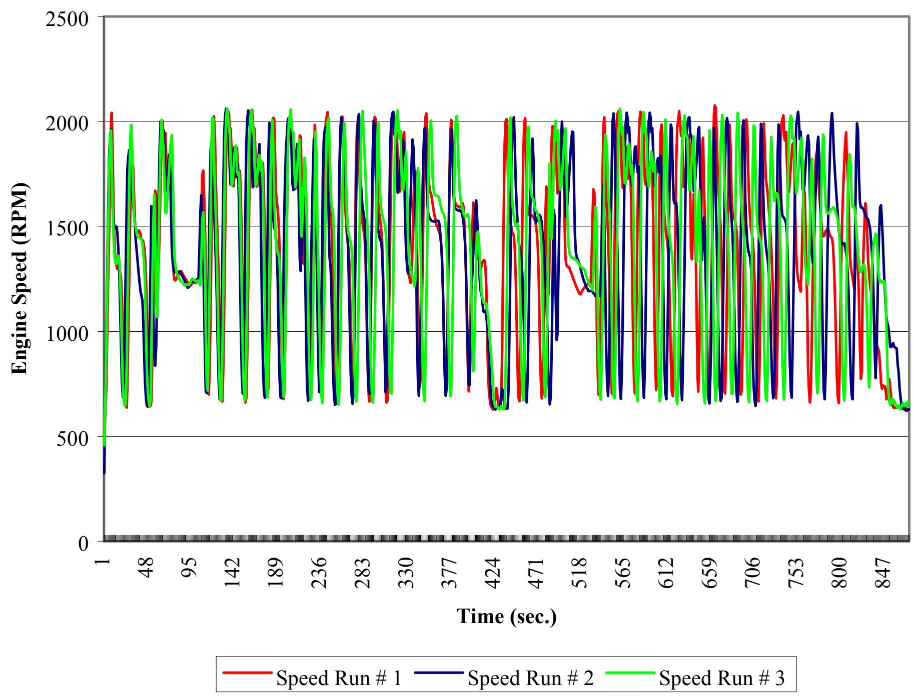


Figure 39 Summary of Engine Speed Profiles of 1995 International Dump Truck (ID # 23659) Baseline Diesel Configuration On-Road Cycle



In order to determine test cycle repeatability, at the conclusion of each test run, an average engine air intake, exhaust temperature, and engine speed value was calculated. Test cycles were regarded as repeatable if these average values did not exceed a +/- 5 % variance. An example of the test cycle repeatability of 1995 International Dump Truck (ID # 23659) is presented in Table 12.

Table 12 Test Cycle Repeatability of 1995 International Dump Truck (ID # 23659) Baseline Diesel Configuration On-Road Cycle

Test Run	Average Engine Intake (SCFM)	Average Exhaust Temperature (^oC)	Average Engine Speed (RPM)
Run # 1	180.03	254.46	1390.24
Run # 2	179.74	251.53	1390.15
Run # 3	178.11	250.84	1389.59
AVERAGE	**179.29**	**252.28**	**1389.99**

7.0 DISCUSSION

As a part of the Houston – Galveston Ozone Non-attainment Area, the City of Houston has established a comprehensive plan to reduce air pollution emissions for each City department. The plan has an overall objective of reducing the emissions of NOx, the largest man-made contribution to ozone precursors, by fifty to seventy-five percent, together with a reduction of fine particulate (PM2.5) by at least 25-33%. A cornerstone of the plan is the Diesel Field Demonstration Project. The study reported here was initiated under the Diesel Project to demonstrate the effectiveness of various cleaner burning diesel fuels as well as diesel emission control devices in reducing emissions from diesel powered equipment operated by the City of Houston.

Under the Diesel Field Demonstration Project a total of twenty-nine units were selected to be representative of the fleet, twenty-six of which were subjected to emissions testing in the field by Environment Canada as described in the previous sections of the report. Table 13 summarizes the technologies that were considered for the program.

Table 13 City of Houston Emission Reduction Program Technology Summaries

COMPANY	PRODUCT	DESCRIPTION
Lubrizol	PuriNOx	Diesel/water blended fuel emulsion with proprietary additive package
Engine Control Systems	AZ Purimuffler	Diesel Oxidation Catalyst with PuriNOx
Ceryx Inc.	QuadCAT	Oxidation and reduction through secondary HC injection
Extengine	ADEC I (SCR/SNCR)	Ammonia reductant and SCR
Extengine	ADEC II (SCR/SNCR + PM Trap)	Ammonia reductant and SCR with additional Particulate Trap
Engelhard Corporation	DPX with EGR	Catalyzed muffler with EGR* (with ULSD)
CleanAIR Systems	Catalyzed Particulate Filter	Catalyzed diesel particulate filter
CITGO Petroleum Corporation	CITGO Emulsion	Diesel/water emulsion blended with proprietary additive package
Johnson Matthey*	Continuously Regenerative Tech.	Diesel Particulate Filter* (with ULSD)
Siemens – Westinghouse*	SINOx	Catalytic Oxidation and Reduction (SCR)

* - Baseline emission levels were determined for the selected vehicles however control technology was not installed

7.1 Emission Results

The emissions that are generated by diesel engines are influenced by three main parameters, the fuel composition, the nature of the operating cycle, and the condition of the engine itself. In this project the focus was on the ability of emulsified fuels, as well as retrofit emission control systems, to reduce specific exhaust components, namely NOx and particulate. The challenge facing the suppliers of these systems is that the mode of operation of the engines can widely vary. The duty cycle itself has a significant impact on the quantity and composition of the exhaust emissions as well as the exhaust temperature, which is so critical for many of these control systems. For example a technology that has been proven for an urban bus application may not exhibit the same performance (emissions and durability) when used in a marine or other non-road application. In this program it is possible that, in many cases, the technologies were applied to specific applications for the first time.

The field emissions evaluation was designed to quantify the emission rates of various exhaust components while the engine was operated in a manner that represented its daily operation. In some instances allowances were made to adjust the operation of the vehicle or equipment to accommodate the requirements of the testing. This was done primarily to enhance the repeatability of the test-to-test results. In each application the emissions were measured with the engine in its original configuration and also following the implementation of the emission control system or strategy.

As previously stated, the primary objective of the Diesel Field Demonstration Project was to evaluate an array of technologies on a diverse range of engine applications, with a target of reducing NOx emissions by 50-75% and PM2.5 by 25-33%. Of the systems tested in this program only four were represented as having the capacity to meet the upper NOx objective, while all were reported as being capable of meeting the particulate objective.

The wider availability of systems designed for particulate control could be attributed to the focus and efforts of the engine and emission control manufacturers to meet the lowered particulate emission standards for highway engines, which went from 0.60 to 0.25 g/bhp-hr in 1991 (and to 0.10 in 1993 for urban bus engines), and also the urban bus rebuild/retrofit program which mandated the upgrading of the particulate emission control. In this latter program, the USEPA, in 1993, published the final Retrofit/Rebuild Requirements for 1993 and Earlier Model Year Urban Buses (*40 CFR Part 85 Subpart O*). At the time, the retrofit/rebuild program was intended to reduce the ambient levels of particulate matter (PM) in urban areas and was limited to 1993 and earlier model year (MY) urban buses operating in metropolitan areas with 1980 populations of 750,000 or more, whose engines are rebuilt or replaced after January 1, 1995.

Under this program the emission levels from a rebuilt engine must be reduced by 25%, relative to the level which the engine was originally certified, or alternatively, meet the 0.1 g/bhp-hr limit. Systems for this program were subjected to rigorous testing by the suppliers to verify their performance claims.

In regards to NOx emission control, the regulations for highway engines have been progressively tightened but perhaps not to the same degree as particulate, as the latter was seen to be more of a direct health hazard than NOx. From 1990 to 1991, the NOx limit was lowered from 6.0 to 5.0 g/bhp-hr, and again in 1994 was further tightened to 4.0 g/bhp-hr. The next major hurdle to the engine suppliers is the 2004 limit where the NOx + HC standard has been re-introduced at a challenging 2.5g/bhp-hr (HC contribution can not exceed 0.5 g/bhp-hr).

7.1.1 Particulate Control

The emission control technologies that were evaluated in this program that were specific to particulate control included oxidation catalysts, diesel particulate filters, and emulsified diesel fuels. Catalyst and filter technologies have been used in diesel applications for quite some time, finding their initial market in the non-road industrial sector in both mobile and stationary engines such as those used in underground mining. The transition to the highway market had been slow until the introduction of the tightened particulate standard in the early 1990's, and the urban bus rebuild/retrofit program. The diesel/water fuels have been available for a number of years, but have only recently been considered as a potential highway fuel.

A summary of the average and range of emission control that was observed during the field-testing for each of the technologies is presented in Table 14. In general the systems were successful in meeting, and exceeding, the objectives of the demonstration program. A rough average of all the technologies yielded a particulate reduction of 55%. However there were instances where technology performance fell short of the manufacturers expectations. In some cases this could be attributed to operational problems with the technology, while in others it is speculated that the technology was not optimized for the particular engine application and the respective duty cycle.

Table 14 City of Houston Emission Reduction Technology Effect on TPM

Company	Product	Description	Expected Reductions[5]	Observed Reductions (min-max)	Average Reduction
Lubrizol	PuriNOx	Diesel/water Emulsion	PM 30 - 50%	24 – 69%	46%
Engine Control Systems	AZ Purimuffler	Oxidation Catalyst with PuriNOx	PM 70%+	58 – 76%	70%
Ceryx Inc.	QuadCAT	Oxidation and reduction through secondary HC injection	PM 90%+	41 – 54%	32%
Extengine	ADEC I	Ammonia reductant and SCR	PM 25 %	27%	27%
Extengine	ADEC II	Ammonia reductant and SCR + Diesel Particulate Filter	PM 75 %+	92%	92%
Engelhard Corporation	DPX with EGR	Diesel Particulate Filter with EGR + ULSD	PM 25%	76 – 83%	79%
CleanAIR Systems	Catalyzed Particulate Filter	Catalyzed diesel particulate filter	PM 85%+	21 – 83%	55%
CITGO Petroleum Corporation	CITGO Emulsion	Diesel/water Emulsion	N/A	41 – 52%	48%

[5] City of Houston: Diesel Field Demonstration Project. Presentation by Dewayne Huckabay

7.1.2 Oxides of Nitrogen Control

The emission control systems that were specific to controlling the NOx levels included exhaust gas recirculation, reduction catalysts, and diesel/water emulsified fuel. As discussed, the NOx control technologies are often reliant upon the existence of other parallel control systems or strategies to facilitate their operation. This could include lowered sulfur content of the diesel fuel where catalysts are sensitive to sulfur poisoning, or the presence of a particulate control system to filter out the coarse particulate matter. In this program the systems were tested in real world conditions so as to evaluate their performance under the fleet operating conditions. Table 15 summarizes the results in comparison to the supplier's expectations.

There was a wide range of results observed during the field-testing with several systems meeting the aggressive program objective of a 50-75% reduction in NOx emissions. In general those systems that had emission reductions below this target did meet the performance levels as stated by the manufacturer. Therefore they were not expected to reach the target from the outset of the program.

The diesel/water emulsions technology was observed to reduce NOx emissions by approximately 30% on average. While this is well below the minimal target of the program, it is an interesting result in that the technology can be applied across the fleet without modification of the individual vehicles or equipment and achieve nearly 50% of the desired overall reduction from the diesel fueled fleet. This would reduce the emissions from City and Contractor owned diesel engines and vehicles from the 1999 estimate of 272.4 tons per year to 190.7 TPY. The introduction of oxidation catalysts (Ceryx Device) as a retrofit control system used in conjunction with the emulsified fuels was observed to increase NOx by up to 19% in comparison to the baseline configuration.

With regards to the retrofit technologies, diesel particulate filters were shown in the project to be effective in reducing large fractions of the particulate emissions and thereby creating the conditions where EGR and other systems could be considered. In this project, the DPX-EGR system achieved NOx reduction of up to 80%, while a catalyzed DPX achieved reductions from 25 to 72%.

The reduction catalysts that were evaluated in the program relied upon secondary hydrocarbon or ammonia injection to facilitate the operation of the catalyst. The results were mixed, with the hydrocarbon injection system resulting in an overall deterioration in the exhaust emissions, while the ammonia based system yielded NOx reductions upwards of 80%.

Table 15 City of Houston Emission Reduction Technology Effect on NOx

Company	Product	Description	Expected Reductions[6]	Observed Reductions (min-max)	Average Reduction
Lubrizol	PuriNOx	Diesel/water Emulsion	NOx 8 – 25%	16 – 41%	30%
Engine Control Systems	AZ Purimuffler	Oxidation Catalyst with PuriNOx	NOx 21%+	18 – 48%	34%
Ceryx Inc.	QuadCAT	Oxidation and reduction through secondary HC injection	NOx 30 – 50 %	Up to 10%	Up to 10%
Extengine	ADEC I	Ammonia reductant and SCR	NOx 25%	78%	78%
Extengine	ADEC II	Ammonia reductant and SCR + PM Trap	NOx 50 – 75%	82%	82%
Engelhard Corporation	DPX with EGR	Diesel Particulate Filter with EGR + ULSD	NOx Up to 80%	78 – 81%	79%
CleanAIR Systems	Catalyzed Particulate Filter	Catalyzed diesel particulate filter	NOx 40 – 70%	25 – 72%	53%
CITGO Petroleum Corporation	CITGO Emulsion	Diesel/water Emulsion	N/A	25 – 28%	27%

[6] City of Houston: Diesel Field Demonstration Project. Presentation by Dewayne Huckabay

7.1.3 Final Comments

This program, led by the City of Houston, is one of the first programs of its type to be undertaken by a major municipality to address the pollution contribution of its in-use fleet to the overall air quality of the region.

During the Houston testing the mass emission rates of hydrocarbons, carbon monoxide, carbon dioxide, oxides of nitrogen, and particulate matter were determined for a range of vehicles and engines from the City fleet. The emission rates were determined while the vehicles and engines were operated over cycles that were representative of their typical operation, using a portable emissions analysis system developed by Environment Canada. The project is unique in that it examined the emissions from various mobile sources while these engines were operated in the field under real world conditions. Previous to this program similar efforts have focused primarily on emission measurements under controlled laboratory conditions. Each vehicle was tested in its original configuration as well as after the installation or implementation of selected emission control technologies that were designed to reduce particulate matter as well as oxides of nitrogen. While this approach to emission characterization has some shortfalls in regards to the degree of repeatability or accuracy in comparison to laboratory studies, the advantage or difference lies in the diverse range of vehicles and engines that can be studied in their normal operating environment.

The structure of the overall program was designed to evaluate a cross-section of technologies on a range of vehicles, and produce the results that can be used by the Region and other stakeholders to evaluate the emission reduction potential, and cost effectiveness, of various air quality strategies. An additional benefit or output of the program is that the baseline data can also be used to fine tune existing emission inventories with real world emission factors.

In summary, the technical objectives of the test program, a 50-75% reduction on NOx, and 25-33% reduction in particulate emissions, was shown to be achievable with retrofit technologies for in-use diesel powered vehicles. Widespread application of some of these technologies may be possible at this time, while other systems may require further engineering and verification.

Diesel emission control system retrofit has been demonstrated as a potential element of the overall air quality management strategy for the Houston-Galveston Region.

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APPENDIX